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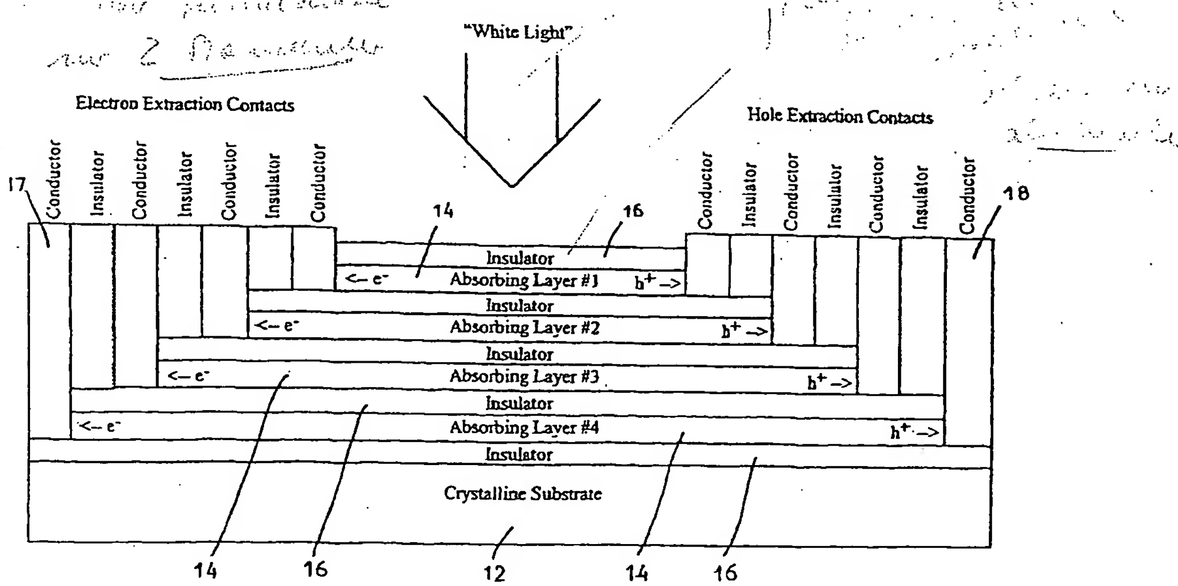

(57) Abstract: A device comprising a number of different wavelength-selective active layers (12) arranged in a vertical stack on a substrate such that the incident light is caused to travel through layers with monotonically decreasing band-gaps. Photons of different energies are selectively absorbed in or emitted by the active layers. Contact means (17, 18) are arranged separately on the lateral sides of each layer or set of layers having the same parameters for extracting charge carriers generated in the photon-absorbing layers and/or injecting charge carriers into the photon-emitting layers. The device can be used for various applications: display, solar cell, imager, light-valve etc. The architecture of the device can be adapted to produce coherent light.

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STACKED WAVELENGTH-SELECTIVE OPTO-ELECTRONIC DEVICE

Field of the Invention

The present invention relates to the field of opto-electronic devices including photo absorption (or detection) and photon emission processes.

Background of the Invention

Many kinds of photo-detectors serve many kinds of particular applications. Two major distinctions can be made: detectors for imaging, not only in the visible range of wavelengths, but also in the infra-red and ultra-violet regions of the electromagnetic spectrum; and power generation, usually designated as Solar-Cells.

Photoelectric devices , like standard solar-cells and detectors for the visible range of wavelength, infra-red, ultra-violet, etc. typically use the same built-in electric field to separate and to collect the generated carriers. The built-in electric field, is generally provided by homojunctions, and in more advanced devices by heterojunctions. This architecture, implies a trade-off between number of generated carriers (which will translate into current), and readout speed; since both are dependent on the thickness of the active film. Another trade-off must also to be made between resolution, and signal amplitude or intensity, that is, the number of collected carriers.

In silicon, there are two major imaging architectures: Charge Coupled Devices (CCDs), and Complementary Metal Oxide Semiconductor (CMOS) technologies.

Coupled Charge Devices (CCDs) are the standard Imagers used in consumer electronics. Most of video cameras and camcorders use a CCDs. Some of the reasons for the widespread use of this technology, are its compatibility and integration with CMOS circuits, the sharing of processes and process equipment with integrated circuit (IC) manufacturing. All the advances in fabrication technologies made in IC production can be directly applied to CCDs. But CCDs have intrinsic limitations in terms of the product spatial-resolution × signal-amplitude × readout-speed, as already mentioned.

CCDs are a collection of MOS capacitors, and the non-negligible density of energetic states in the mid-gap, originating in the unavoidable defects at the Si/SiO_2 interface, can be an important source of electron-hole recombination.

Although CCD Imagers, have enjoyed a great commercial success, they are not without limitations. For example, signal reading is a serial process, signal amplitude, resolution and speed are coupled, and have to be traded-off. On top of this, fairly high voltages need to be used.

CMOS Imagers, are now becoming a serious competition for CCDs in some consumer electronics products like "digital still cameras". Advantages of CMOS Imagers over CCDs, are its simpler process flow and even easier integration with Planar CMOS technology, and lower operating voltage. On the other hand, CCDs still produce better images than CMOS sensors.

From the signal amplitude (or intensity) point of view, the active medium, where photon absorption causing electron-hole pair generation takes place, should be as thick as possible to absorb as much radiation as possible. In detectors where the direction of carrier collection is the same as the incoming radiation, this would mean extremely long carrier collection times, and non-negligible recombination rates.

If, on the other hand, speed is what is sought, the active layer thickness has to be reduced and therefore the number of photons absorbed will be also reduced, thereby weakening the readable signal and decreasing the signal-to-noise ratio.

For CMOS Imagers there is a non-negligible area of the pixel which is occupied by the MOS Field-Effect Transistor. Naturally this area does not contribute for electron-hole pair generation, and therefore, as pixel sizes are reduced, this can become an important factor.

One technological problem common to CCDs and CMOS Imagers is the low efficiency detection/absorption of red light in silicon. This problem is directly related to the band-gap of silicon and the wavelength of the color red. As a consequence, it takes considerable more silicon active volume (where absorption takes place) for a useful signal-to-noise ratio of the red component. Some collateral effects are: increased cross talk (with adjacent active areas for other colors/pixels) and slower signal readout. For the same reason, neither CCDs or CMOS Imagers are appropriate for Infra-Red detection.

Shown in **FIG. 1** is a schematic cross section of "Planar CMOS Imager". Such a device is made with several extra steps being added to the fabrication of standard CMOS circuits. Naturally special design rules and layout structures are necessary, as well as extra steps to place the color filters (color dye) over the active areas assigned to those colors.

This device is basically a pn-junction, absorbing light that has been filtered, so that only photons within a fairly narrow range of wavelengths generate electron-hole pairs in the pn-junction of the pixel corresponding to the desired color. That pn-junction is usually the source-to-well junction of a MOSFET. When the gate is "Off", the charge at the source is isolated from the drain. By turning the gate of the MOSFET "On", the charge becomes available at the drain, for readout purposes.

A full color pixel is composed of three color dye, corresponding to the three primary additive colors. The techniques used to place the color dye, have inherent alignment issues, which can be barriers to further downscaling of the pixel sizes, that is, to increase resolution.

However, pixel size scaling is possibly more problematic due to poor signal-to-noise ratio, because signal strength (number of generated electron-hole pairs) scales with area, but noise doesn't. The color dye filter in each primary color pixel absorbs all wavelengths not corresponding to its own color, thereby "wasting" all those photons.

Since the band-gap of silicon is fixed and different colors are just photons with different energies, it means that not all colors will be absorbed with the same efficiency by the silicon pn-junction. For example, it is well known that the photons of red color, having the longest wavelength, penetrate many hundreds of nanometers into the silicon active area, while the photons of blue color are absorbed within a few tens of nanometers.

Another mass market photoelectric device, is the solar-cell. Silicon solar-cells are also based on the capability of the built-in field of a pn-junction to separate electrons from holes and also to collect them at spaced apart electrodes.

Once photons have generated the electron-hole pairs, recombination is the killing factor for the efficiency of those devices. There are several recombination mechanisms, which are responsible for the poor efficiency. A reason for non-negligible recombination is that, from the point of generation until the point of collection, a very large portion of both types of carriers (traveling in opposite directions), have to cross extended regions where they are minority carriers.

The bulk silicon material that carriers have to cross, has a non zero defect density. Defects introduce energetic states in the band-gap, thereby exponentially increasing the probability of recombination. Another mechanism is Auger recombination, which is not originated in defects, but it is intrinsic to bulk semiconductor physics.

One possible improvement upon standard technology, regarding the first recombination mechanism is the "Multilayer Thin Film Solar Cell". However, such a device is still made with homojunctions (same band-gap related limitations), and the lateral ohmic contacts are not trivial in providing a good "selectivity" between electrons and holes.

For solar-cells there are two fundamental and contradictory requirements:

- The band-gap of the absorbing medium should be as small as possible to absorb as many photons as possible, and therefore generate as many electron-hole pairs as possible.
- For the purpose of as large as possible "open-circuit voltage", the band-gap of the absorbing medium should be as wide as possible.

When a photon with energy larger than the band-gap of the active medium is absorbed, the excess of energy, is converted into kinetic energy carried by the electron-hole pair. In indirect band-gap materials like silicon, this excess of energy is almost entirely converted into heat inside the semiconductor. Therefore, from the open-circuit voltage standpoint, the excess of energy is wasted.

Single band-gap, homojunction solar-cells, like standard silicon solar-cells, have two major drawbacks:

- The pn-junction built-in field, is used for two purposes: electron-hole separation, and carrier collection. The active medium has to be thick enough, in order to absorb as many photons as possible. The thicker the layer, the weaker the electric field, and when an electron-hole pair which is generated far away from the metallurgical junction, one of the carriers - electron or the hole - will have to travel a very long distance to the point where it is going to be collected. There is a large probability of this carrier to recombine, because it will be a minority type of carrier, throughout most of the distance until it is collected.
- For photons with energy much larger than the band-gap of the semiconductor, the excess of energy is wasted into heat generation, rather than converted to a large "open circuit voltage".

Another insurmountable factor for "bulk" type of devices, is Auger recombination. Recent studies indicate that this particular recombination process can be suppressed in devices with type-II band-alignments ["Mechanisms of Suppression of Auger Recombination Processes in Type-II Heterostructures", Georgy G. Zegrya and Aleksey D. Andreev, App. Phys. Lett. 67(18), 30 October 1995, 2681-2683; "Auger-Free Si-SiGe Quantum Well Structures for Infra-Red Detection at 10 µm", E. Corbin, K.B. Wong and M. Jaros, Solid-State Electronics, Vol. 39, No. 2, pp. 237-241, 1996; "Optical Spectra and Auger Recombination in SiGe/Si Heterostructures in 10 µm Range of Wavelengths", E. Corbin, C.J. Williams, K.B. Wong, R.J. Turton, M. Jaros: Superlattices and Microstructures, Vol. 19, No. 1, 1996, pp. 25-32]. Such band-alignments are possible with combinations of multiple layers of $Si_{1-x}Ge_x$, $Si_{1-y}C_y$ and $Si_{1-y-x}Ge_xC_y$ alloys. These types of layers do not integrate well with planar technology, but that are straightforward to include in vertical devices made by low temperature epitaxial deposition.

Light-Valves are devices supposed to controllably be either transparent or opaque to a given wavelength or range of wavelengths. The control of the opaque/transparent states can be either by other light beams or by electrical fields. Until now it has been advantageous to have electrically controlled Light-Valves as it is easier to interface with CMOS logic, DRAM, etc. which are still fully electrical and have not yet purely optical counterparts.

The most commonly used type of Light-Valves are Liquid Crystals (LCs), which have found their major application in Flat-Panel Displays (FPDs). Other types of Light-Valves like "Suspended Particles" (SPs) are also thought to have a chance to compete with LCs in order to improve the performance and cost of FPDs.

The field of Micro-Opto-Electronic-Mechanical-Systems (MOEMS) is also offering alternative materials, device and process flow architectures, promising to compete with LCs and SPs for some applications and to offer unique solutions for certain others.

In addition to Flat-Panel Displays, there are other fields of great technological and economic importance, where Light-Valves can play a fundamental role. One of these other fields is optical networking, and in particular optical routing. It is well known that optical fibers are the medium of choice for ultra large bandwidth. However, the speed at which optical fibers can carry information has not been matched at the switching/routing level. Until recently the light signals had to be converted to electrical signals, processed and routed, and converted to light beams again to reach the final destination. Recently, there have been announcements of technical breakthroughs, which are supposed to enable "all-optical routing". It is known in the public domain that these future "all-optical routers" are going to be built around MOEMS and with Light-Valves like LCs.

LCs are not truly solid state, are notorious for their slow switching speed and have many other limitations like large operating voltages (typically more than 15 Volts), sensitivity to temperature, require polarizers, poor "viewing angle", etc. LCDs which can work either at transmission or reflection, have had major difficulties in being produced with high pixel counts, and in a cost-effective manner for sizes large enough to compete with CRT technology for TVs and computer monitors. LCDs have a complex fabrication sequence and inherent problems to scale down pixel size, especially for color displays, as there are important alignment problems between frontside and backside panels. Also, the most commonly used substrates, made with amorphous or poly silicon on glass, do not possess the required electrical performance to enable VLSI-type of electronic circuitry. For these and other reasons, LCDs are not capable of attaining the pixel size and density suitable to display high resolution diffraction patterns required for high quality holography. High resolution diffraction gratings require a 2D array (a matrix) of sub-wavelength (of the "color" to act upon) "pixels".

MOEMS (or MEMS), though solid-state devices, rely on moving mechanical parts, which immediately places an upper limit on how fast and reliable they can be. They also require large operating voltages, typically more than 10 Volts, and are not fully compatible with standard CMOS processes, or at least not yet.

LEDs and LASERs are fundamental to many important applications in many and varied fields. They are the fundamental components for fiber optics communications for example. These devices are fabricated with compound semiconductor materials, having direct band-gaps and enabling heterojunction or band-gap engineering.

Even though it has been many years now that it has been possible to make device quality heterojunction structures, the indirect nature of the band-gap has made impossible to make LEDs and LASERs with the silicon-germanium materials system.

The incompatibility of the III-V materials used to fabricate the LEDs and LASERs, and the silicon material system which enjoys a tremendous advantage for high density microelecronics, has been a barrier to increase the performance and functionality of systems requiring both LEDs/LASERs and high density logic and memory circuits.

Summary of the Invention

It is an object of the present invention to provide a novel device architecture that overcomes several of the limitations of the photo-electric devices using known CCD and CMOS technologies.

Another object of this invention is to provide opto-electronic devices that are usable in high performance systems requiring the use of LEDs and/or LASERS.

The device architecture according to this invention comprises a stack of different active (photon-absorbing and/or photon-emitting) layers arranged on a substrate such that the incident light travels layers with monotically decreasing band-gaps , whereby photons of different energies are selectively absorbed in or emitted by the active layers. Separate contacts are adapted to extract the charge carriers generated in the photon-absorbing layers and to inject charge carriers into the photon-emitting layers.

The wavelength selectivity, that is the selectivity in photon-absorption or photon-emission of the layers in accordance with photon energy, can be realized in different ways using Inter-Band Transitions (Transitions from valence to conduction band) or Inter-Subband Transitions (Transitions from a quantized level to another one within the same band). Selecting and/or adjusting the parameters which control the wavelength sensitivity of the active layers in the stack permit to implement devices that suit a wide range of needs or applications.

The device architecture concept of the invention allows implementing high-performance photo-electric and opto-electronic devices independently of the choice of any materials system. However, and due to the obvious and economic relevance of silicon technology, the invention will be set out in more detail when referring to layers compatible with silicon.

Advanced layer deposition techniques enable the fabrication of very sophisticated doping and heterojunction profiles in the direction of epitaxial growth. Quantum Wells which only require reduced dimensionality in one direction are then easy to be made with such techniques. If and when the fabrication of other quantization structures (e.g. Quantum Wires,

Quantum Dots) would become easy, the invention could make use and take advantage of quantization in more dimensions.

The present invention does bring many advantages over the prior art technology in terms of wavelength-selectivity and operating voltage (typically 1 Volt), it provides truly solid-state devices with no moving mechanical parts and devices having a wide "viewing angle". These features will bring many advantages for FPDs and optical network components.

Further, the invention introduces innovative photo-detector concepts, which can be engineered towards many different applications. Some of those applications are based on the device being designed to operate as an Imager to be incorporated in mainstream consumer electronics products, like Digital Still Cameras, Video Cameras, Camcorders, Solar-Cells, etc. Due to the multi-spectral capabilities, it can also function as an Imager for non-visible wavelengths (e.g. IR and UV), with applications like night-vision equipment, through-fog vision.

The same device can also be optimized for other functionalities, like wavelength-selective Light-Valves. The architecture remains the same but there may be some engineering tradeoffs to optimize it for the targeted task. The Light-valves can also operate in visible spectrum, and/or with the IR and UV wavelengths. Some applications of the Light-Valves are for displays, optical switches, optical modulators, optical routers, with the latter being especially useful for optics communications. For some of these applications the setup may require the combination of the light-valves with wavelength-selective reflectors, made possible with Photonic Band-Gap (PBG) materials.

A particular and unique advantage of the invention is that the same device or panel implementing the invention can alternatively serve as an Imager, a Solar Cell and a Light Valve. It is worthy of note that a light valve incorporating the invention is not only usable in displays, but also in opto-electronics, for instance Electronic Mirror or Digital Mirror.

Further, when being operated at the suitable frame rate, a device incorporating the invention can alternate the function of Imager and Light Valve, and with appropriate system integration, the same surface will alternately capture or display images. If the images are the same, then the device functions as a mirror. Actually, the same images can be obtained after some signal processing, for example. It should be noted that the invention allows simultaneous imaging in the invisible range of wavelength and therefore totally new functionalities can be built upon such a capability.

Of course, the images do not have to be same. For example, as a part of a telephone set (either wireline or wireless), this capability would enable videoconferencing with image capture (to be sent to the other party) and image display of the other party.

Implementing the Imager and Light Valve layers vy using the Inter-Subband Transitions, that is with very narrow spectral ranges, enables the simultaneous and non-interfering operation of Imager and Light-Valve functionality if at least a small differentiation exists in the wavelengths of the primary colors used for the Imager and for the Light Valves.

The same device can also be optimized for other functionalities, like wavelength-selective Light-Valves. The architecture remains the same but there may be some engineering tradeoffs to optimize it for the targeted task. The Light-valves can also operate in visible spectrum, and/or with the IR and UV wavelengths. Some applications of the Light-Valves are for displays, optical switches, optical modulators, optical routers, with the latter being especially useful for optics communications. For some of these applications the setup may require the combination of the light-valves with wavelength-selective reflectors, made possible with Photonic Band-Gap (PBG) materials.

The present invention is also capable to be optimized to function as a light emitter rather than light absorber. Some particular may require the combination of the SWASP active layers with micro-cavities and PBG materials, thereby to enhance the performance and enable emission of coherent radiation (LASER). Consequently, the present invention has the potential to solve the incompatibility problem encountered in the fabrication of LEDs /LASERs, as stated earlier herein, and it enables a qualitative jump in performance, functionality, compactness and price of systems with LEDs/LASERs and ULSI circuitry, by fabricating all these components on silicon substrates.

These and other features and advantages of the invention will become more apparent from the following description and the accompanying drawings.

Brief Description of the Drawings

FIG. 1 shows a cross-sectional view of a prior art planar CMOS imager;

FIG. 2 shows a cross-sectional view of the device architecture according to the invention;

FIG. 3 shows a 2-dimensional schematic of the band-diagram depicting a cut parallel to the quantum well layers;

FIG. 4 illustrates the application of the invention for use as a solar cell, without specifying the materials;

FIG. 5A illustrates the application of the invention for use as an imager integrated with a solar-cell , wherein the Imager is to operate on Inter-Band Transitions in bulk or superlattice active layers;

FIG. 5B shows the layer stack of FIG. 5A together with the corresponding band-gap sequence and wavelength selectivity thereof;

FIG. 6A illustrates the application of the invention for use as an imager integrated with a solar-cell, wherein the Imager is to operate on Inter-Subband Transitions in quantized structures like "Multiple Quantum Wells" active layers;

FIG. 6B shows the layer stack of FIG. 6A together with the corresponding band-gap sequence and wavelength selectivity;

FIG. 7 is a 3D schematic band diagram of a Quantum Well, showing the bands of the epitaxial insulator responsible for the formation of the electrostatic potential well, the bands and subbands of the active layer, and the bands of the lateral contact insulator;

FIGS. 8A, 8B, 8C show band-diagrams along cuts in the structure, parallel to the QW layers for different bias conditions to passively depleting the supply of holes to be photo-excited;

FIGS. 9A, 9B, 9C show band-diagrams along cuts in the structure, parallel to the QW layers for different bias conditions to actively depleting the supply of holes in the low-energy subband;

FIG. 10 is a schematic diagram of an exemplary arrangement according to the invention for Light-Valves.

Detailed Description of the Invention

Referring to **FIG. 2**, there is schematically shown the device architecture according to the invention. This architecture is called SWASP , an acronym for Stacked WAvelength-Selective Photo-detector, although the device can operate as a photon-absorber or a photo-detector with an identical layer structure . The SWASP structure of the invention consists in a set 10 of different layers arranged in a vertical stack on a substrate 12, whereby photons of different energies are selectively absorbed in or emitted by the different layers. The layers are arranged such that the incident light travels layers with monotically decreasing band-gaps.

The stack includes epitaxial (pseudomorphic) semiconductor active layers 14 (with varying band-gaps) and insulator layers 16. Each active layer (or set of layers with the same parameters), is capable of absorbing a specific wavelength or a range of wavelengths. For each layer, or sets of layers with the same parameters, contacts 17, 18 are provided laterally. The contacts are also made separately for electrons and for holes at the opposite ends of the same active layer or set of active layers.

The insulator layers 16 are positioned to separate regions absorbing different wavelengths, and therefore the charge carriers generated by a given wavelength or set of wavelengths are kept electrically insulated from the ones generated by other wavelengths. For other reasons, as it will be seen later, it can happen that insulating layers are also placed within the active region of a given wavelength or range of wavelengths.

The selectivity in photon-absorption or photon-emission according to photon energy can be realized or implemented in several different ways and by operation on Inter-Band Transitions (IBT) , that is on transitions form valence to conduction band, or on Inter-Subband Transitions (IST), that is on transitions from a quantized level to another one within the same band.

The architecture concept is independent of any materials system. However and due to the obvious technical and economic relevance of silicon technology, the examples and embodiments refer to layers compatible with silicon.

Advanced layer deposition techniques enable the fabrication of very sophisticated doping and heterojunction profiles in the direction of epitaxial growth. Quantum Wells which only require "reduced dimensionality" in one direction, are then easy to be made with such techniques. Quantum Wires and Quantum Dots require "reduced dimensionality" also in one or two lateral directions, respectively.

Therefore, examples of quantized structures will, by default, mean Quantum Wells. However, this should not be seen as a conceptual limitation. If and when it becomes equally easy to fabricate Quantum Wires and Quantum Dots, the same concepts can (with suitable adaptations) be also used to implement these new device concepts.

In the following, the invention will be described in the case where the active layers are to be photon-absorbing layers. The same considerations apply however to the case where the active layers are to be photon-emitting layers.

Wavelength-Selectivity with Inter-Band Transitions (IBT)

Band-gap engineering of "thick films" (with "bulk-like" properties) can provide "Low-Pass Filters" for the photon absorption. All photons above a certain energy, which is related to the band-gap magnitude and nature of the absorbing medium, are absorbed. The material is transparent for photons below that threshold in energy.

Each film (or set of films with the same properties), in the stack has a different "absorption-edge" and appropriate thicknesses, in order to absorb nearly all photons with energy above its band-gap.

In order to make a filter for a narrow range of wavelengths, two different absorbing media are required. The "spectral purity" of the of the filter is proportional to the difference in band-gaps between the two different media.

With band-gap photo-absorption, electrons are promoted from the Valence Band (VB) into the Conduction Band (CB), thereby creating a hole in the valence band of the absorbing medium. For bulk semiconductors, the energies allowed to the charge carriers (eigenvalues), are in an energy continuum starting at lowest energy points of the CB and VB.

A photodetector made with "Short-Period SuperLattices" (SLs) should also behave like a "Low-Pass" filter, where the cut-off wavelength is determined by the gap between the Conduction and Valence "Minibands".

With SLs, the Mini-Gap between the Conduction and Valence Minibands can be varied in almost continuous way between the band-gaps of the elemental materials used to fabricate the superlattice, by controlling the structural parameters governing the superlattice.

Due to the "Low-Pass Filter" nature of band-gap absorption ("bulk" and SLs), the exact sequence of absorbing media needs to follow a rule. The "absorption edge" must increase monotonically, from the bottom to the top of the layer stack. The incoming electromagnetic radiation containing all wavelengths (also called "White Light"), in the Visible, Ultra-Violet (UV) and Infra-Red (IR), must penetrate the stack from the top, where the absorption-edge is wider.

As electromagnetic radiation progresses through the stack of absorbing layers, at each layer in the stack, is stripped of its shorter wavelengths (higher energy photons). Therefore only the longest wavelengths (lowest energy photons) reach the bottom of the stack. The charge carriers generated in each "wavelength filter" (which may consist of more that one absorbing layer) are collected laterally. Electrons are collected at one end, and holes are collected at the other end of the device. Electrons and holes are separated and driven towards the opposite contacts by a lateral electric field, which can be built-in, or externally applied, or both.

With the quantization effects originated by reduced dimensionality of the active medium, the eigenvalues will no longer be in the continuum at the edges of the Conduction and Valence Bands, but will be discretized, and shift away from those band-edges (with geometric progression).

The fabrication of Quantum Wells (QWs) can be achieved with a semiconductor material being sandwich between two large electrostatic potential barriers. The barriers can be provided by, for example, another semiconductor or, better still, by an insulator. Consequently there will be a shift of the eigenvalues to higher energies (as the QW thickness is reduced), of the minimum of the energy of the photons that the semiconductor can absorb, thereby causing an apparent increase in the band-gap of the absorbing material (a blue-shift).

There is another important difference with regards to bulk materials: not only the band-gap appears to become wider, but the QW photo-detector <u>is not</u> a "Low-Pass Filter", since not all photons with energy larger than the difference between the lowest energy subbands in the CB and VB will be absorbed.

The reason for this, is that the quantization that causes the apparent "widening" of the band-gap also opens "gaps" between the subbands inside the Conduction Band and inside the

Valence Band. Even for the allowed states (eigenstates) there are Quantum Mechanical rules that allow or forbid certain transitions. Within the allowed transitions some are more favorable than others (greater "oscillator strength").

Depending on many details like the full band-structure of the photo-absorbing material, and properties of the QW, it may be possible that within a wide range of wavelengths, only one particular wavelength is absorbed, in delta-like fashion. The true physical picture is a very complex one, and here it will be only with rough and simplified (or simplistic) approximations are used.

In Quantum Wells (QWs), as the film thickness decreases, the eigenvalues increase (referenced to the respective band-edges), and therefore the band-gap of the QWs increase. A single QW may not absorb all the photons with energy above the band-gap (may not have enough "active volume"). Then, rather than just one, it may be required to fabricate Multiple Quantum Wells (MQWs) with identical specifications. The exact number of QWs required will be different for each range of wavelengths to be filtered, and is determined by how many photons (of a given wavelength or wavelengths) must be absorbed.

For very long wavelengths, other types of photo-detectors are also used, like for example the Schottky-barrier detector. This detector makes use of heterojunction barriers, either between a metal and a semiconductor, or between degenerately doped and lowly doped semiconductors. A "semiconductor-only" Schottky-barrier detector, should have a straightforward integration of its layers at the bottom of an epitaxial layer stack, and become a "normal" part of it.

Wavelength-Selectivity with Inter-Subband Transitions (IST)

Inter-Subband Transitions can only be implemented with "reduced dimensionality" structures. This kind of detector is unipolar, because charge carriers are not moved from one band of the crystal into another, but rather switch energetic levels inside the same band (Conduction or Valence). The different subbands originated by quantization effects; and are independent (to a first order of analysis) of the band-gap (magnitude and type) of the materials used to make the quantized structures. This presents very interesting opportunities for materials whose band-gap structure is not adequate for optoelectronics, and therefore are ruled out for "conventional" optoelectronic devices.

Photodetectors making use of this kind of physics have already been utilized for Infra-Red (IR) and Far-Infra-Red (FIR) detection. Also, the "Quantum Cascade Laser", utilizes such mechanism (Inter-Subband Transition) for photon emission.

The complete physical picture is also a very complex one, but for the purpose of the present disclosure, it is sufficient to say that there are also specific rules governing the

transitions between subbands. Some of those transitions are forbidden, while others are allowed, and of these some have higher "oscillator strengths" than others (as expected).

It can be said that the most favored transitions are those between the lowest level (provided that it is populated with enough carriers) and the level immediately above it (in energetic terms), and that transitions between subband 1 and 3 or between subband 2 and 4 are forbidden. For example, the transitions between the lowest subband (n=1) and the next subband (n=2), has 96% chance of happening, leaving only 4% for all other possible transitions.

It is therefore possible to engineer Inter-Subband Transitions, by designing quantum wells with the appropriate settings, regarding quantum well symmetry, shape (square, parabolic, triangular, etc.), film thickness (well width), depth, doping, etc.

Inter-Subband Transition (IST) devices, not only their absorption-edges can be engineered, but also they are not "Low-Pass Filters", since all photons with energy lower OR higher than the difference between eigenstates, are not absorbed. Only one particular wavelength is absorbed, in delta-like fashion. Due to the reduced active volume of the Quantum Wells, it maybe necessary to fabricate identical Multiple Quantum Wells in order to increase signal strength.

This property is extremely useful for designing photo-detectors of great spectral purity for a given wavelength. Actually they do so while being transparent to all other wavelengths. The application of this feature to visible wavelengths, enables novel devices and device configurations.

There is one very important remark to be made. In principle, Inter-Subband transitions can take place for photons of any energy, from the IR, through the Visible, and even to the UV portions of the electromagnetic spectrum. However, the energy of the photons in the visible, ranges from about $1.8eV$ (for the color Red) to about $3.1eV$ (for the color Violet). Thus, IST devices for the visible range of the electromagnetic spectrum, need potential wells deeper than $3.1eV$. In fact that value should be exceeded as much as possible, for the well to be an approximation to the ideal "infinitely-deep" Quantum Well, as good as possible. Therefore, very wide band-gap materials are needed to make the very large electrostatic potential barriers.

In order to make quantum wells deeper than for example $4eV$, either Ultra-Wide band-gap semiconductors, or ultra-wide band-gap insulators, are absolutely required. This requirement immediately sets some restrictions on the materials that can be used to implement these devices. Naturally, the use of insulators to form the QWs, would pose insurmountable barriers for the contacts in conventional-design QW detectors.

This remark is a good introduction and motivation to the next subchapter of the present disclosure.

Selective Lateral Contacts by Workfunction Engineering

The layer stack structure of the invention incorporates epitaxial insulators in different positions, performing different roles. In some cases, it will be just to electrically insulate films absorbing different wavelengths, so that they do not become electrically shorted, and in some other cases the insulators are required to make the QWs themselves (especially when very deep potential wells are needed).

Therefore, the conventional contacting scheme, where one type of carriers is extracted at the top and the other type at the bottom of the epitaxial layer stack, would not work here. The solution lies with the fabrication of lateral contacts to the different layers that are electrically insulated from each other. Also, the extraction of electrons and holes out of each of these layers is to be made separately. Moreover, the contacts to the electron and hole extraction points, should in general, be made with different conductive materials, having different workfunctions (there could be a few exceptions).

It is easy to understand and visualize different contacts to different materials lying in different planes/levels of the epitaxial stack. But contacts to the same film (e.g. a QW) or sets of films (e.g. MQWs), with the ability to selectively, at different points, extract (or inject) electrons OR holes rather than electrons AND holes, is not so obvious, especially because some of the active layers are non-doped.

By "Workfunction Engineering", it is possible to separate electrons from holes, inside the MQW layers, and collect them at opposite sides of those layers. The built-in field originated by the difference in workfunctions, does skew the bands of the absorbing layers in the plane perpendicular to the direction of epitaxial growth, thereby forcing electrons to one side, and holes to the other side of the MQW layers. In this way, charge carriers can travel to the points of collection, parallel (rather than perpendicular) to the MQW planes, therefore without crossing the MQW barriers. This is what enables MQWs with ultra-wide band-gap semiconductors and insulating layers.

There are several ways to implement the workfunction engineering mentioned above. The range of workfunctions provided by metals goes from a little less than $2eV$ up to more than $6eV$. This provides workfunctions clearly above the CB and below the VB of silicon.

Another possibility to implement workfunction engineering is to use heavily doped layers of different semiconductors with varying band-gaps. Here there is some more freedom to provide different workfunctions, as different levels of doping degeneracy can be fairly easily controlled during the deposition process of the contact material.

However, many of the metals and semiconductors that can provide such degree of "Workfunction Engineering", may originate serious interfacial issues when coming in direct contact with silicon and/or other absorbing layers. In most cases these will form silicides, altering the original workfunction to something that typically falls inside the band-gap of silicon, thereby defeating the purpose of using those materials.

There is an alternative way of still providing "Workfunction Engineering" and avoiding the potential interfacial issues with the layers of the structure. It consists in simply providing an ultra-thin layer of an insulator like SiO_2, Si_3N_4, $SiON$, Al_2O_3, etc., between the "contacting conductor" (most likely a metal) and the side wall of the absorbing layer(s).

Rather than making contacts by metal-semiconductor junction, the contact will be made by "Direct Tunneling" through a very leaky Metal-Insulator-Semiconductor (MIS) system. The fact that the insulator layers are ultra-thin does enable very large "Direct Tunneling" current densities, and therefore an efficient extraction of electrons and holes out of the absorbing layer into the contact materials.

Recently, MIS (or MOS) systems with ultra-thin insulator layers have been a very important topic of research in solid state electronics, namely advanced CMOS for $0.1\mu m$ generation and below. The reasons are that standard CMOS scaling implies the thinning of the gate insulator (SiO_2) for each new generation of the technology. Gate lengths around $0.1\mu m$ or operating voltages of around $1Volt$ and below, require SiO_2 thickness to be less than $2.5nm$. At this point Direct or Ballistic, rather than Fowler-Nordheim, Tunneling is the mechanism responsible for transport across the insulator. Very large current densities are then inevitable, because in this thickness regime, current density is exponentially dependent on the insulator thickness.

The driving force for that research is to find ways of minimizing the current density through the insulator, while increasing the capacitance of the MIS system. It seems that the solution is to replace SiO_2 with other insulators having larger values of the dielectric permittivity, so that for the same capacitance the films can be thicker, and tunneling currents significantly reduced.

A by-product of this research is the experimental verification that extremely thin films of SiO_2 and Si_3N_4, have a much higher breakdown field than the "bulk-like" values of thicker films, and that in fact, it is even difficult to define the breakdown point. These ultra-thin films are capable of enduring extremely large tunneling current densities, apparently without detectable damage, precisely because Ballistic Tunneling implies the absence of scattering within the insulator film, and therefore less probability to cause damage.

The present invention takes advantage of the knowledge generated by this research, but to the opposite purpose of what motivated it in the first place: use the very-thin insulator layers to enable high tunneling currents. They provide inter-position layers, which act as physico-chemical barriers between silicon and metals that ought not be interfaced directly with silicon.

The question of uneven tunneling currents due to the large differences in electron and hole masses, and in conduction and valence band offsets, can be solved or compensated through the suitable independent choice (for electrons vs. holes) of the insulator film composition and thickness. For example, SiO_2 has a band-gap of $9eV$. The barrier height between Si and SiO_2 for electrons is $3.2eV$, and for holes is $4.7eV$. On the other hand, Si_3N_4 has a band-gap of $5eV$. The barrier height between Si and Si_3N_4 for electrons is $2.2eV$, but for holes is only $1.7eV$! For Si_3N_4, the barrier height for holes is less than the one for electrons .

It should be reminded that this "Workfunction Engineering" is enabled because electrons and holes can have different contacts. In fact the optimization of the contacts (insulator film composition, thickness, and electrode workfunction) can be independently carried out for electrons and holes, for each of the wavelength filters, having different band-gaps and eigenvalues.

This optimization is supposed to maximize the electron flux and suppress the hole flux through the electron contact, and symmetrically the maximize of the hole flux and suppress the electron flux at the hole contact. This is possible because of the wide ranges in barrier heights, between the absorbing medium and different insulator materials on one hand, and on the other, also due to the wide range of workfunctions available for the contact materials.

For the "electron contact" the optimal parameters are:

1) Small barrier height for electrons
2) Large barrier height for holes.
3) Small workfunction electrode. Workfunction of contact electrode, at the same level or higher of the relevant eigenvalue in the CB of the absorbing medium.

For the "hole contact" the optimal parameters are:

1) Large barrier height for electrons
2) Small barrier height for holes.
3) Large workfunction electrode. Workfunction of contact electrode, at the same level or lower (larger WF) of relevant eigenvalue in the VB of the absorbing medium.

If very narrow band-gap materials were chosen for the detection of very long wavelengths, then there might be a problem with the electron and hole extraction from such layers. If

metals having the workfunctions somewhere in the gap of such narrow gap material were used, it would mean a very small difference in workfunctions, or even the same workfunction for the electron and hole electrodes. Therefore, it might even be necessary to apply an external bias in order to extract the carriers efficiently out of the absorbing layers.

However, this scenario is not inevitable. With optimized parameters for electron and hole contacts, like what is described above, it is possible to design lateral MOS structures on the narrow band-gap material, where the workfunctions of the electron and hole electrodes are outside the band-gap of silicon by a considerable margin.

The case of charge carrier extraction from QWs or MQWs with "Inter-Subband Transition", is somewhat more complicated but also provides even more interesting opportunities. Since "Inter-Subband Transition" devices are unipolar, either electrons or holes are to be extracted, but not both. Moreover, using this photo-absorption mechanism for energetic photons like those in the Visible and UV ranges, makes very difficult to apply "Workfunction Engineering" schemes similar to those just described for "Band-Gap Transition" devices. However, something very special can be obtained.

So far the assumption has been that the insulating-barrier films to be positioned laterally, between the photon-absorbing films and the contacting metal, have fairly wide band-gaps, in any case significantly wider than the one of the absorbing medium.

FIG. 3 shows a 2-dimensional schematic of the band-diagram depicting a cut parallel to the quantum well layers (perpendicular to the direction of epitaxial growth). On the left hand side the lateral "contact insulator" is SiO_2, and on the right hand side the "contact insulator" is Si_3N_4. Both sides have the same metal contact with a workfunction in the middle of the band-gap of silicon.

For very deep QWs (MQWs), the eigenvalues (E_{V1}, E_{V2}) are very far from the (Valence) band edge of the active region (semiconductor material). Because of this, the definition of "contact barrier-height" needs some special attention too. As an example let us assume that the subband of the QW which receives the photo-excited charge carriers (E_{V2}) has an eigenvalue, which when referenced to the edge of the valence band, is given by the sum $\Delta_2 + \Delta_3 + \Delta_4$. The "barrier-height" seen by these photo-excited carriers when they approach the lateral (at the right-hand side) interface is the difference between the band-edge of the "contact insulator" and the eigenvalue of the QW subband where they have been promoted to. This difference is given by $\Delta_1 - (\Delta_2 + \Delta_3 + \Delta_4)$ and for the case depicted on the right-hand side of FIG. 3, the difference (barrier height) is negative.

In conclusion, with the appropriate choice of "contact insulator", the carriers will not see any barrier at all (negative barrier-height), and therefore are free to move in the lateral

direction, and "fall" to the "contact metal". This is the case for MQWs with Inter-Subband Transitions in the Valence Band, where Si_3N_4 is the "contact insulator". In this case, the charge carrier extraction, although made through an interposing "contact insulator", does not involve tunneling (the contact insulator can be "thick"), because the photo-excited carriers (and only these) are energetically beyond the band edge of the "contact insulator".

For carriers in those high-energy eigenstates (E_{V2}), the "contact insulator" provides physio-chemical barrier, but not an electrostatic potential barrier. However, this "contact insulator" is indeed an electrostatic potential barrier for the carriers in the lowest subband (E_{V1}), where they reside before absorbing photons.

The "contact insulator" plays a very important role also for these carriers in the lower subband: it keeps them inside the QW (or MQW). That would not be the case if direct metal-semiconductor contacts were envisaged, that is, without the interposition of the "contact insulator".

Even though the interposition of a "contact insulator" was motivated to prevent potential interfacial reactions between materials, and thereby provide more freedom in "Workfunction Engineering", it revealed itself having a major impact on device physics in contacting IST devices.

It must be pointed that the QWs ought not be looked at as "floating body" kind of problems. The reason is that at least one of the "contact insulators" is thin enough to enable large tunneling currents. For this range of thickness, these are "leaky insulators", meaning that the wave functions of the charge carriers, either those in the QW or those in the "contact metal" fully penetrate the insulator and "reach" the other side of the barrier. Therefore the QWs are not truly electrically isolated, and therefore floating, as it would be the case with "thick" lateral insulators.

SWASP Solar-Cell

A multiple band-gap photo-detector as described above herein can absorb the same photons that the single band-gap device can, and then more because of the possibility of narrower band-gaps. But the single band-gap device (like standard Solar-Cells) wastes all the excess of energy that photons have with respect to its band-gap, and therefore that excess of energy is not reflected in the "Open-Circuit Voltage".

Already for a long time, has been predicted that the "ideal maximum efficiency" increases with increasing number of band-gaps connected in a series scheme. It can be as high as 72%, which is the double of the "ideal maximum efficiency" of single band-gap mono-crystalline silicon pn-junction solar cells. While in neither case will the cells attain this "ideal

maximum efficiency", it is reasonable to expect that the ratio of efficiencies might not deviate too much from this factor of 2 in favor of Multiple Band-Gap Solar-Cells.

The "series" arrangement of the Cells, can be best achieved by in-situ doping during the hetero-epitaxial deposition of the several layers with different band-gaps. If for some reason the "Open-Circuit Voltage" of the entire epitaxial stack was too large (for example to recharge the battery), then it would be fairly easy to make lateral contacts to some of the layers in the stack. This would enable parallel connections between groups of layers (with equal "Open-Circuit Voltage") from the stack, thereby increasing the "Short-Circuit Current".

FIG. 4 schematically shows the structure for a solar cell, without specifying the materials. The implementation with materials compatible with silicon, is fairly easy and straightforward to obtain band-gaps narrower that silicon's, but it is more difficult for band-gaps wider than silicon's.

Narrower band-gaps than silicon's, can easily be obtained with the epitaxial deposition of random alloys and/or superlattices of $Si_{1-x}Ge_x$, $Si_{1-y}C_y$, $Si_{1-z}Sn_z$ or any combination of them as $Si_{1-x-y-z}Ge_xC_ySn_z$.

Wider band-gaps than silicon's, can be obtained in many ways. However, not all of those are suitable due to the special requirement of ohmic contacts between all stacked layers with different band-gaps. Clearly, the fabrication of Quantum Wells with ultra-wide band-gap semiconductors or insulators would not enable the necessary ohmic contacts across the layers in the stack. However if the Quantum Well barriers between wells become thin enough (only a few atomic layers) so that a superlattice is formed, the wavefunctions of charge carriers overlap across several wells, thereby generating "Minibands".

It should be possible to achieve a smooth increase in band-gap, through "Minibands" originated by "Short-Period SuperLattices" (SLs). Provided that it is possible to make highly doped regions at the bottom and top of a given superlattice (for a given Miniband), it should be possible to fabricate structures corresponding to the idealized description of a multiple band-gap solar-cell. Possible materials for such superlattice with silicon can be Al_2O_3 (Sapphire), CaF_2 (Calcium Fluoride), CdF_2 (Cadmium Fluoride), CeO_2 (Cerium Dioxide), as there is abundant scientific literature on their hetero-epitaxy on silicon .

<u>SWASP Imager</u>

Imagers can be designed making use of either Inter-Band Transitions (IBT) or Inter-Subband Transitions (IST). An imager designed for IBT in bulk or superlattices can be looked at like a "pixelized" multiple-Band-Gap Solar-Cell, with gaps ranging from more than $3eV$, to just a few K_BT (less than $0.1eV$). The larger the number of different absorbing

layers, that is, the higher the number of different band-gaps present in the layer stack, the smaller the intervals in which the entire electromagnetic spectrum to be absorbed, is divided into. This signifies that each layer will absorb only a narrow range of wavelengths. If the different absorbing layers were looked at like "Low-Pass" Band-Gap "color" filters, it could be said that they would have a high "spectral purity".

If the layers absorbing the wavelengths corresponding to the three primary colors (either additive or subtractive), have high enough spectral purity, and if it was possible to contact them individually, then the "Imager" and "Solar-Cell" functionalities could work simultaneously without conflict.

For a multiple-band-gap solar-cell with a large number of intermediate band-gaps, the loss of the contribution of just three of wavelengths, would not cause any significant reduction in the overall efficiency. On the other hand, the "Imager" functionality can be self-powered, because of all the amount of light coming into the photo-detector, only those three wavelengths corresponding to the primary colors, are not used for the "Solar-Cell" functionality. Naturally what has just been said about the three primary colors in the visible range also applies to wavelengths in the UV and in the IR spectra.

The area of the pixel (of the active regions) remains basically unchanged and therefore can be said to be independent of the number of wavelengths to be filtered for imaging purposes and that are therefore subtracted from those contributing to the "Solar-Cell functionality". The reason for this, is because the area necessary to make individual contacts to a reasonable number of "wavelength" filters, is a very small portion of the total area of the pixel.

The spectral purity of a given wavelength (or color) filter is determined by the energy difference to the band-gap of the layer immediately above it. For example, the spectral purity of the filter for the color Green, is given by the difference in band-gaps between the Green-filter itself and the filter to absorb all the colors between Green and Blue. Due to a likely non-linearity in photon absorption, as a function of film thickness and photon energy, this physical picture may be somewhat oversimplified. However, it makes the point that due to the nature of "Low-Pass Filter", Band-Gap Filtering does require absorbing layers for intermediate wavelengths, between the color filters that demand high spectral purity, like the ones used for imaging.

There is an obvious interest in making filters for the three primary additive colors, Red, Green, and Blue (R, G, B), which can be implemented (from top to bottom) in the following way (**FIG. 5A**):

- Top of the detector (where light is coupled into the device)

  Solar-Cell for the wavelengths in the UV.

Filter for a particular wavelength in the UV.

Solar-Cell for the wavelengths between Blue and UV.

Filter for the color Blue.

Solar-Cell for the wavelengths between Green and Blue.

Filter for color Green.

Solar-Cell for the wavelengths between Red and Green.

Filter for color Red.

Solar-Cell for the wavelengths between IR and Red.

Filter for a particular wavelength in the IR/FIR

- Bottom of the detector

As it can be seen, the list of layers of the epitaxial stack required to perform RGB filtering for imaging purposes, contains not just the three RGB layers, but other three for the "inter-primary-color" filtering. The generated carriers in these layers, by those photons that have no use for RGB imaging, must be collected separately from the ones generated in each of the RGB layers. But rather than just being wasted, and since they come for free, they can as well be used to generate electricity. Actually, they can be used to self-power a camera.

Again, for all wavelength filters, the electrons and holes are collected laterally and separately. For a given color filter, electrons and holes have separate contacts, with different materials (and insulators. The previously listed sequence of layers and band-gaps can be implemented with silicon-compatible materials and technologies in the following manner **(FIG. 5B):**

- "Wavelength filters" with a band-gap narrower than silicon's, can be obtained with Group IV alloys and/or superlattices containing all or just a few of the following elements $Si_{1-x-y-z}Ge_xC_ySn_z$ (with varying stoechiometries).
- "Wavelength filters" with a band-gap wider than silicon's, can be obtained with superlattices of Si or $Si_{1-x-y-z}Ge_xC_ySn_z$ (with varying stoechiometries), Al_2O_3, or CaF_2, or CdF_2, for example. Since superlattices require extremely thin films, strain relaxation should not be a problem.
- Insulators to electrically insulate different layers, can be several, of which the following seem to be the best candidates: Al_2O_3 ($E_g \cong 12eV$), CaF_2 ($E_g \cong 12eV$), and CeO_2, are insulators, all with large conduction and valence band offsets to silicon. CdF_2 ($E_g \cong 8eV$) has a negative barrier height for electrons with silicon .

Actually, given the compatibility of growing Al_2O_3 on silicon, it can be used as a buffer layer, thereby enabling the growth of other materials (thin or thick films), that normally are

not compatible for direct deposition on silicon. Al_2O_3 (Sapphire) has been the substrate of election to grow AlN, $AlGaN$ and GaN ($E_g \cong 3.5eV$) to make HEMTs, LEDs and LASERs, operating in the blue and violet regions of the electromagnetic spectrum.

The possibility of using these direct band-gap semiconductor, either as a photo-detector or a photo-emitter (LED or LASER), fully integrated with CMOS on a 200mm (and soon on 300mm) wafers opens up tremendous new technical and economical possibilities.

An Imager working on IST and/or IBT in quantized structures has a few advantages over the previous example. The first is the potentially much higher "spectral purity", as Quantum Mechanical selection rules enforce that only a particular wavelength is absorbed (naturally there is always a small spread). This is much more elegant and precise than selecting a wavelength through the difference in band-gap of two materials. Another advantage is that this kind of photo-absorption is not a "Low-Pass Filter" but rather more like a delta in absorption, that is, the QWs are transparent to all other photons with energy higher or lower than the ones to be absorbed.

This enables the architecture depicted in **FIG. 6A** to be implemented, wherein the "Imager" layers are on top of the "Solar-Cell" layers. This arrangement is certainly beneficial and applicable to photons with large energies, like the ones in the Visible and UV ranges. However, for Imaging with photons in the IR and FIR ranges of the spectrum, it may be better to position those layers under the layers performing the Solar-Cell functionality. Naturally the Band-Gap engineering of the Solar-Cell layers will be such that the wavelengths to be used for IR/FIR imaging will not be absorbed.

This simplifies the design of the stack, and therefore its fabrication, as there are no films in the middle of stack that need special contacts schemes to provide the "primary colors" for the Imaging functionality. However, from a materials perspective it becomes more difficult to implement as the photon energy gets higher and the required potential well needs to be deeper, that is, the QWs need to be narrower.

- Top of the detector (where light is coupled into the device)

  Filter for a particular wavelength in the UV.

  Filter for the color Blue.

  Filter for the color Green.

  Filter for the color Red.

  Layers for Multiple-Band-Gap (from IR to UV) Solar-Cell.

  Filter for a particular wavelength in the IR/FIR.
- Bottom of the detector

This list of layers is considerably simpler and, in fact, it is highly modular as there is a decoupling of the Imaging (Visible and UV) from the Solar-Cell layers. The preferred embodiment of this concept shown in **FIG. 6B**. The QWs/MQWs are formed by Ultra-Wide Band-Gap materials known to be epitaxially compatible with silicon. Of such long list, the ones perceived to be the best candidates are: Al_2O_3 ($E_g \cong 12\,eV$), CaF_2 ($E_g \cong 12\,eV$), and CeO_2 are insulators, all with large conduction and valence band offsets to silicon, and CdF_2 ($E_g \cong 8\,eV$) has a negative barrier height for electrons with silicon .

A simplified calculation will now provide the kinds of numbers (for quantization effects) possible with these materials. The eigenvalues depend on the QW film thickness and the carrier masses, which in turn are a function of the populated valleys, and therefore of how strong the quantization effects are. Due to the very large band-gap of Al_2O_3 ($E_g \cong 12\,eV$), and the very large conduction and valence band discontinuities between silicon and Al_2O_3, this structure can be modeled by the "infinite square well" approximation, which is treated in any basic textbook on quantum mechanics.

Sine functions are appropriate to be used as the wavefunctions of the charge carriers in the infinitely deep electrostatic potential well:

$$Z(z) = \sqrt{\frac{2}{L_z}} \sin\left(\frac{n_z \pi}{L_z} z\right)$$

where $Z(z)$ is the envelope function in the z-direction (direction of confinement), L_z is the width of the QW film between the electrostatic barriers, and $n_z = 1, 2, 3, ...$ is the subband index. The allowed energy values in the well (the eigenvalues) are given by:

$$E_{n_z} = \frac{\hbar^2}{2m_z}\left(\frac{n_z \pi}{L_z}\right)^2 = \frac{\hbar^2 \pi^2 n_z^2}{2 m_z L_z^2}$$

where m_z is the carrier mass in the direction perpendicular to barriers, that is, in the direction of the epitaxial layer deposition.

The calculation can be far more complicated, because charge carriers residing in different subbands may have different masses. This is so because the carrier energy can be increased (larger eigenvalue), because of occupation of a higher subband, or because for the same subband index has a larger eigenvalue due to decreased QW width.

The difference between eigenvalues is given by ($E_{C0} + E_{C1}$)-($E_{V0} + E_{V1}$), where E_{C0} is the "bulk" Conduction Band edge, E_{V0} is the "bulk" valence band edge, E_{C1} is the lowest energy eigenvalue in the Conduction Band, E_{V1} is the lowest energy eigenvalue in the Valence Band.

From the previous expressions, it follows that the large subband eigenvalues can be obtained by either reducing the charge carrier mass or by reducing the QW film thickness. The first being a material parameter should provide a criteria for the selection of potential candidates for the QW film.

For Inter-Band Transitions, this is complicated as the material parameters are quite relevant for these transitions. Masses of carriers in the VB and CB are quite different, the degeneracy and valley occupation of CB and VB also further complicate matters a great deal.

On the other hand, for Inter-Subband Transitions, the materials parameters are canceled, and transitions only depend on either the CB or the VB.

It happens that pure germanium has very small "light hole" mass, and that strain (to silicon lattice) even lifts the degeneracy with the 2 "heavy hole" bands. Therefore, very thin films of $SiGe$ (ideally pure Ge) strained to Si, between very large barrier height for holes, should provide a promising system for the fabrication of devices working with high energy photons, like those in the visible range. The Ge MQWs could sandwiched between Al_2O_3 barriers.

So it turns out that the simple calculations for the eigenvalues as a function of the QW width, for "light-holes" of strained Ge, are not such a bad approximation to more sophisticated calculations.

To make delta-like absorbers (with Inter-Subband Transitions) for the Infra-Red (IR) range, many semiconductor heterostructures could be used, due to the small band-offsets required. Typically wide band-gap semiconductors would be used to form the QWs. Among the several possibilities, $GaAs$, AlN, GaN, and several of their alloys have been used and usually are the best candidates.

However, in the visible range, photon energies range from about $1.8eV$ for Red color ($\lambda \approx 700nm$), to about $3.1eV$ for Violet ($\lambda \approx 400nm$). This is clearly out of reach for all of them, except maybe AlN.

On the other hand the very deep potential wells required for these photon energies can be provided by the fabrication of silicon-based QWs with epitaxially compatible insulators like some of the already mentioned. In fact, experimental measurements reveal that QWs made with sandwiches of $CaF_2 / Si / CaF_2$ form CB wells $2.3eV$ deep, and VB wells $8.7eV$ deep! Therefore, it seems that Inter-Subband Transitions in the VB, are possible for extremely energetic photons, found in the UV and DUV regions of the electromagnetic spectrum.

The photon energy ($\hbar\upsilon$) needs to be exactly $\hbar\upsilon = E_2 - E_1$. The difference between the second and first eigenvalues is simply given by:

$$\hbar\upsilon = E_2 - E_1 = \frac{\hbar^2\pi^2}{2m_z L_z^2}\left(2^2 - 1^2\right) = 3 \times \frac{\hbar^2\pi^2}{2m_z L_z^2}$$

The following are some calculations to show the Ge QW parameters for photons in the visible range. For ultra-thin MQWs, it is feasible to deposit pure (pseudomorphic) Ge films strained to the silicon lattice.

$$\hbar^2 = \left(1.05457 \times 10^{-34}\right)^2 Js$$

$$m_0 = 9.10939 \times 10^{-31} Kg$$

The eigenvalues as function of subband index, carrier mass and QW width are given by:

$$E_{n_z}[eV] \approx \frac{\left(1.05457 \times 10^{-34}\right)^2 \times (3.1416)^2 \times (n_z)^2}{1.6 \times 10^{-19} \times 2 \times m_z^* \times 9.10939 \times 10^{-31}} \frac{1}{L_z^2}$$

Therefore the QW width as a function of the energy difference between the first and second subbands is given by:

$$L_z[nm] = \sqrt{\frac{0.7530861 \times \left(2^2 - 1^2\right)}{2m_z\left(E_2 - E_1\right)[eV]}}$$

In Ge, the mass of "light holes" is $m_z(lh) = 0.044 \times m_0$, and of "heavy holes" is $m_z(hh) = 0.28 \times m_0$

- Photons of color Blue

  $\hbar\upsilon \approx 3.0eV = E_{V2} - E_{V1}$,

  With "light-hole" mass

  $L_z = 2.9nm$,

  $E_{V1}(lh) = 1.00eV$,

  $E_{V2}(lh) = 4.00eV$,

  For the same QW width, the "heavy hole" subband yields

  $E_{V1}(hh) = 0.16eV$,

  $E_{V2}(hh) = 0.63eV$,

  $E_{V3}(hh) = 1.41eV$,

  $E_{V4}(hh) = 2.51eV$,

  $E_{V5}(hh) = 3.93eV$,

  $E_{V6}(hh) = 5.65eV$,

- Photons of color Green

$\hbar\upsilon \approx 2.4eV = E_{V2} - E_{V1}$,

With "light-hole" mass

$L_z = 3.3nm$,

$E_{V1}(lh) = 0.79eV$,

$E_{V2}(lh) = 3.14eV$,

For the same QW width, the "heavy hole" subband yields

$E_{V1}(hh) = 0.12eV$,

$E_{V2}(hh) = 0.49eV$,

$E_{V3}(hh) = 1.11eV$,

$E_{V4}(hh) = 1.98eV$,

$E_{V5}(hh) = 3.09eV$,

$E_{V6}(hh) = 4.45eV$,

- Photons of color Red

$\hbar\upsilon \approx 1.8eV = E_{V2} - E_{V1}$,

With "light-hole" mass

$L_z = 3.8nm$,

$E_{V1}(lh) = 0.59eV$

$E_{V2}(lh) = 2.37eV$,

For the same QW width, the "heavy hole" subband yields

$E_{V1}(hh) = 0.09eV$,

$E_{V2}(hh) = 0.37eV$,

$E_{V3}(hh) = 0.84eV$,

$E_{V4}(hh) = 1.49eV$,

$E_{V5}(hh) = 2.33eV$,

$E_6(hh) = 3.35eV$.

The "heavy hole" subbands with largest index (for each color) could provide, the energy difference necessary for the absorption of photons in the visible. However, because of

the selection rules already mentioned, it is much less likely to have such transition than between first and second "light hole" subbands.

Now that the exact parameters of the MQWs have been found, other aspects of the devices (Imagers by Inter-Subband Transitions), need to be specified.

The issue of the lateral contacts has a very interesting situation here:

Photons of color Blue ($\hbar\upsilon \approx 3.0eV$), $L_z = 2.9nm$, $E_{V1}(lh) = 1.00eV$, $E_{V2}(lh) = 4.00eV$,

Photons of color Red $\hbar\upsilon \approx 1.8eV$, $L_z = 3.8nm$, $E_{V1}(lh) = 0.59eV$, $E_{V2}(lh) = 2.37eV$,

Photons of color Green $\hbar\upsilon \approx 2.4eV$, $L_z = 3.3nm$, $E_{V1}(lh) = 0.79eV$, $E_{V2}(lh) = 3.14eV$,

As it can be verified, all first subbands for the three primary colors are below $1.0eV$ from the VB edge. All second subbands for the same three primary colors are more than $3.1eV$ from the VB edge. As seen before, the distance from the VB edge of Si_3N_4 to Si is only $1.7eV$. To this $1.7eV$ is added the further discontinuity of strained Ge. But since even for pure Ge, the VB edge moves up by less than $1.0eV$ the eigenvalues of the second subband are always in a position such that the Si_3N_4 layer does not present any electrostatic potential barrier at all. On the other hand, all eigenvalues corresponding to the first subbands (for the three primary colors) do see a potential barrier presented by the Si_3N_4 film.

FIG. 7 is a 3D schematic band-diagram of a QW, where it is clear that the lateral "contact insulator" does not represent a potential barrier for the carriers residing in a higher subband.

The first subband, needs to be populated with holes as much as possible. This achieves two things: the first is that it prevents Inter-Band Transitions (as there aren't enough electrons in the VB to be promoted of the CB), and does supply incoming photons of the "right wavelength" with chance of being absorbed through Inter-Subband Transition (IST) and promote a hole into the second subband. Because of all this, it is better to have the MQW highly p-type doped, that is, to have an internal supply of holes. Naturally has photon absorption takes place, there is a depletion of the holes in the lowest subband, originating a space charge layer. The supply of holes into the first subbands (the ones closest to the VB edge), is going to be accomplished by high direct tunneling currents through an ultra-thin insulator.

For instance, in "Physics of Semiconductor Devices", 2nd Edition 1981, Wiley & Sons, Figure 19b on page 540, S.M. Sze shows an example of how to inject/extract electrons from the VB which is equivalent to extract/inject holes into VB. Having this in mind, it is possible to choose the workfunctions for the left-hand side and right-hand side contacts, in order to minimize the magnitude of the applied voltage to inject holes into the first subband in the VB. This can be engineered and optimized for each of the primary colors.

The IST device is unipolar, and in the present embodiment only holes are relevant for the operation of the device. Holes need to be injected into the lowest subband, at one side of the MQW layer stack. Those holes that under go a transition into the second subband (through the absorption of a photon whose wavelength is dictated by the MQW parameters), are extracted at the opposite side of the MQW layer stack. Those holes that remain in the first subband should not leave the MQW.

These conditions require a "contact insulator" with low barrier height for holes Si_3N_4 is perhaps the best candidate. Since hole injection is achieved through tunneling, and hole extraction just "drift-diffusion", then it means that the Si_3N_4 film at the injection point will be much thinner than the Si_3N_4 film at the extraction point (where thickness is not relevant).

It is possible to have an electric built-in field that drives holes in the second subband into the extraction terminal. For the injection terminal, it is convenient to have a small workfunction (like n+ poly Si), and for the extraction terminal, it is convenient to have a large workfunction (like p+ poly Si).

The external applied bias (if necessary) just reinforces the built-in field, that is, the positive polarity is applied at the terminal with small workfunction, and the negative polarity is applied at the terminal with large workfunction.

The first bound state should be fully occupied at all times, simultaneously, the second bound state should be fully depleted. The current that flows between these electrodes (left and right hand side) gives a direct measure of the number of photons absorbed, and therefore of the intensity of light in that particular color.

The parameters of the QW set the eigenstates and eigenvalues, that is, select the wavelengths to be detected. The lateral contacts select which subbands are seeing a lateral potential barrier and which do not.

<u>SWASP Light-Valves</u>

A semiconductor material, is capable of absorbing photons, provided that they have energy larger than its Band-Gap, provided that there are enough carriers to absorb the photons, and provided that the energy levels that they are supposed to occupy (after the absorption) are not full. Therefore, photon absorption can be controlled not only by material parameters (like band-gap and absorption edges), but also by parameters related to charge carrier density and level occupancy (population statistics), which can be controlled with applied bias.

The control of the occupancy of energy levels (population modulation), can be achieved in different manners. There is one very important physical quantity called "Density of Sates", which is the number of states (along with degeneracy factors) per unit of volume

and per unit of energy. It is advantageous to have structures with reduced dimensionality (Quantum Wells, Wires, Dots), because the "Density of States" (DOS) of quantized structures makes the "population control" easier. For example, the DOS of a Quantum Well determines that much less charge carriers are necessary to drastically change the relative position of the Chemical Potential with respect to the eigenvalues, than with the DOS of "Bulk".

The combination of three factors will make possible to make "Light-Valves" with Quantum-Well based photo-detectors:

- Photon absorption does not (does) take place depending on what particular energy levels (eigenvalues) are (are not) occupied;
- Easy modulation of the population in those eigenstates if the absorbing medium has a reduced "Density of States";
- Modulation of the population with extraction/injection through externally applied bias, helped by built-in fields provided by "Workfunction Engineered" lateral contacts to the stack of MQWs.

Therefore, the condition of opacity (photon absorption) requires that the eigenstates (that carriers are promoted to, when a photon is absorbed), to be as depleted as possible. The condition of transparency (non-absorption) requires those eigenstates to have as many carriers as possible. Maximum "dynamic range" or "contrast ratio" of the "Light-Valve", is obtained for opacity with zero occupation of the eigenstate and transparency with full occupation of the same eigenstate.

The capability of modulating the opacity/transparency of a given layer for a range of wavelengths, provides the functionality of "Wavelength-Selective Light-Valves". This "Light-Valve" functionality does not require polarizers, and therefore allows more light to go through the device when in the "transparency state".

<u>Light-Valves" by "Inter-Subband Transitions</u>

The similarity with Imagers goes into the deepest levels. The physics of the absorption (opacity) are exactly the same ones of the SWASP Imager. For those reasons, the same calculations regarding QW composition and depth will be skipped.

It should be kept in mind that the definition in terms of wavelengths for the three primary colors (additive or subtractive) are not universal. Therefore, it is possible to have a SWASP Imager and a SWASP Light-Valve with the respective MQWs designed for RGB absorption, but in slightly different wavelengths.

Due to the similarities with the SWASP Imager, the only point that needs to be covered for the Light-Valve functionality, is the question of controlling the opacity/transparency with voltage.

Three mechanisms for modulating absorption/non-absorption of photons are possible:

A) Passively depleting the supply of holes to be photo-excited. This would amount to just not injecting any holes into the low energy subband, as photons (of the right wavelength) keep promoting holes to the high energy subband. The low energy subband eventually becomes empty, and therefore no more photons can be absorbed.

B) Actively depleting the supply of holes in the low energy subband, can be done with an applied bias to extract holes out of the lowest energy subband, by direct-tunneling them out of the MQWs across the left hand side ultra-thin insulator. This would be like a reinforcement of the passive depletion of holes from the lowest subband. The "re-enforcement mechanism", should result in much faster switching times, especially under low intensity illumination conditions.

C) A third mechanism to prevent photon absorption, it to fill all states to which photo-excited carriers are supposed to jump into. This can be done by actively blocking photo-excited holes from being extracted from the high-energy subband into the right hand side electrode. This action results in a saturation of the high-energy subband with photo-excited holes. In this case, even when there is ample supply of holes in the low-energy subband, there is just no room for more in the high-energy subband, and therefore photons cannot be absorbed. Holes can be prevented from being extracted from the high-energy subband, by impeding drift-diffusing towards the right-hand side and sliding onto that electrode. An externally applied bias driving those photo-excited holes towards the left-hand side insulator/electrode blocks them from extraction at the right hand side. This mechanism requires the left hand side insulator to have the valence band edge such that carriers cannot drift-diffuse to the left hand side electrode, that is, a valence band edge deeper than the eigenvalue of the high energy subband in the QW. For example SiO_2, does fulfill this condition.

Therefore, the condition of opacity (photon absorption) requires that the high-energy subband (the one carriers are promoted to, when a photon is absorbed), to be empty or as depleted as possible. The condition of transparency (non-absorption) requires either the low energy subband to be empty of holes and/or the high-energy subband to have as many carriers as possible (highly populated with holes). The capability of modulating the opacity/transparency of a given layer for a range of wavelengths, provides the functionality of "Wavelength-Selective Light-Valves".

If symmetry in applied bias was required, then the best choice would be to have on both lateral contacts, the same workfunction. In this case, it would be useful to have a workfunction which would be aligned with the lowest-energy subband of the MQW (see the

band diagram). Since each color has different eigenvalues, it is conceivable to choose different metals (with different workfunctions) tuned for each of the primary colors.

FIGS. 8A, 8B, 8C, show qualitative band-diagrams along cuts parallel to the QWs, for different bias conditions, for the ""Mechanism #2" described above.

FIGS. 9A, 9B, 9C, show qualitative band-diagrams along cuts parallel to the QWs, for different bias conditions, for the ""Mechanism #3" described above.

SWASP Light-Valves for Displays

Wavelength-Selective Light-Valves are an unique consequence of the physics employed in this device. No other Light-Valve technology employed today in the fabrication of Flat-Panel Displays has this property. Together with "Wavelength-Specific" or "Wavelength-Selective" Reflectors, a completely new kind of Solid-State Reflection Flat-Panel Display Technology becomes possible.

Due to the nature of the physical effects involved and charge extraction/injection architecture, it is reasonable to assume that this will be a very fast switch between opacity and transparency states, and that it will have a memory effect. In the context of a Flat-Panel Display, this indicates that the structure of the invention as a "Light-Valve" could be driven by a "Passive-Matrix", rather than requiring an "Active-Matrix".

Actually, such Wavelength-Selective Light-Valves are extremely similar to the Imagers described above herein. The difference lies with the required capability of controlling the photon absorption with an applied voltage.

SWASP Light-Valves for Optical Interconnecting & Networking

FIG. 10 shows the schematic of an exemplary arrangement for "Switching" and/or "Amplitude Modulation" and/or Multiplexing/Demultiplexing, and/or Routing with a number of SWASP Light-Valves. This arrangement works by simply controlling the transparency & opacity states of a number of SWASP Light-Valves positioned as a 2D array on a low-loss planar waveguide. The arrangement can work with the 2D arrays of light-valves on just one side or on both sides of the planar waveguide.

When a Light-Valve is in the transparency mode for a given wavelength, photons of that particular wavelength can travel through it with little or no absorption. When the Light-Valve is in the opacity mode a particular, photons of that particular wavelength do are absorbed, and therefore the signal amplitude is strongly reduced. The incoming and outgoing signal(s) can reach the "modulator" either by an optical fiber or some other kind of waveguide. Therefore, the sources of photons for each of the wavelengths (LASERs), can operate in a continuous mode and are not required to do the modulation themselves.

Once coupled and confined in the planar waveguide, the incoming light beams suffer many reflections from the internal walls of the waveguide, so that each port, that is, each element of the 2D array, receives a fraction of the intensity (i.e., number of photons) of the original light beams. The control of the Light-Valves allows or forbids the propagation of photons (of the different wavelengths) through said Light-Valves.

This scheme does not route all the photons of the incoming light beams into a single optical path, but rather, distributes the incoming light beams through all possible optical paths. Therefore, through the command of the transparency/opacity states of the Light-Valves, there is control of which optical paths allow propagation of the light beams, and which do not. Because the outgoing light beams have just a fraction of the intensity of the incoming light beams, regeneration of the optical signals after each port is likely to be necessary.

It should be emphasized that the capabilities just described are available to many wavelengths working simultaneously, because the Light-Valves are wavelength-selective. Because of this wavelength-selectivity of SWASP Light-valves, a single port could be in the "transparent" state for some wavelengths, and in the "opacity" state to others. Therefore it is even possible to have full bi-directionality, provided there is no conflict with the selection of wavelengths "going in", and "coming out". Therefore this can also accomplish wavelength-division multiplexing and demultiplexing.

This is an "all-optical" routing scheme, because even though the photons directed to the non-selected optical paths, are photo-absorbed, that is, converted into electricity, the light beams travelling through the selected optical paths, do so without conversion to electrical signals at any point.

With this architecture, the routing can be "point-to-point", if just one Light-Valve is in the transparency mode, or "point-to-multipoint" if many Light-Valves are "transparent" at the same time. Again, because of the wavelength-selectivity, it is possible to have point-to-point routing for one "color" and point-to-multipoint for another color or color(s).

The intrinsic architecture of this setup, multiple functionalities, like Switching, Amplitude Modulation, Multiplexing/Demultiplexing, and Routing, are fulfilled by a single and very compact architecture.

When using Diffraction patterns, reflectors (wavelength-selective or simple mirrors) are positioned behind a stack of "Light-Valves" for multiple wavelengths. The Light-Valves are patterned into 2D arrays, where the pixels have lateral dimensions smaller than the wavelength of the light to be controlled.

The 2D array elements (or pixels) are commanded by an Active-Matrix of electronic elements (for example MOSFETs) which will individually switch On/Off states of all Light-Valves for all wavelengths. This "Active-Matrix" needs to be made with very dense and very

high-speed transistors, so that the system speed limitation is determined the switching speed of the Light-Valves, not of the transistors.

Coherent light of different wavelengths is provided externally, as it would be the case with the light beams coming from optical fibers or other types of waveguides.

The routing of light beams of different wavelengths is achieved by directing all photons of the incoming light beams into a single optical path for a point-to-point connection, or into many different optical paths for point-to-multipoint connections.

"Beam steering" and "beam-shaping", are made possible only by a diffraction grating with sub-wavelength features. The direction and characteristics of the steered/shaped beams can be dynamically changed, through the Active-Matrix control of the pattern produced by the set of SWASP Light-Valves in the On and Off states.

For example, the most common wavelengths used in fiber optics communications are 1310nm and 1550nm. The microelectronics industry is already capable of producing features much smaller than these dimensions. Critical dimensions of 180nm (0.18μm) are now (mid 2000) routinely used in production of CMOS products, while 0.15μ and 0.13μm are promised to become available in the very near future. These critical dimensions are about 10 times smaller than those wavelengths used for fiber optics communications, and therefore should enable the routine fabrication of SWASP Light-valves small enough to be diffraction gratings for those wavelengths.

The dynamic control of the diffraction pattern, changes the transparency and opacity states of the sub-wavelength-sized 2D array elements (or pixels). For Light-Valves in the opaque state, photons are absorbed, and therefore a black spot is created. For Light-Valves in the transparent state, photons are not absorbed.

For a reflection system, when light beams are not absorbed in the Light-Valves, mirrors positioned behind the Light-Valves reflect them back with the desired direction and shape. The mirrors behind the Light-Valves should preferentially be wavelength-selective, which can be made with Photonic Band-Gap (PBG) layers or materials. The Light-Valves and PBG Reflectors can then to be "tuned" to the exact same set of wavelengths.

Because of the wavelength-selectivity of both the Light-Valves and of the Reflectors, it is possible to have simultaneous different diffraction patterns for different wavelengths, enabling simultaneous and independent and simultaneous "beam shaping" and "beam steering" of different wavelengths.

Other light-valve technologies, like liquid crystals, can perform some of the functionalities of the SWASP Light-Valves. However, SWASP Light-Valves present many advantages, derived from being an "All-Solid State" solution.

A SWASP-based system, may have a transparent material between the two opto-electronic planes. Light-Valves made with LCDs, have some limitations regarding thickness of the full system. LCDs require two panels with a few millimeters of spacing in-between, filled with liquid crystals.

Because the routing is accomplished with switching elements, producing a diffraction grating, the same routing elements can also perform switching and amplitude modulation. The combination of these functionalities into a single device is only useful and advantageous, because of the high intrinsic switching speed of the SWASP Light-Valves. This combination should bring enormous advantages in terms of compactness and cost, over the more conventional solutions, like Liquid Crystal Light-Valves, electrical modulation of LASERs, and Light-Valves made with MOEMS – Micro-Opto-Electronic-Mechanical-Systems).

The physical mechanism for absorption is Inter Subband Transitions (IST), whereby a photo-excited carrier (electron or hole) is promoted to a higher potential energy level within the same band (Conduction or Valence, respectively). This mechanism is intrinsically faster than Inter Band Transitions (IBT), whereby an electron is crosses the forbidden band-gap from Valence to the Conduction band, when absorbs a photon. Both of these mechanisms are orders of magnitude faster (typical times are less than a nanosecond) than Liquid Crystal Light-Valves, which have typical switching times of milliseconds, or any other technology making use of mechanical motion like those of MOEMS.

This is a passive device, which may require signal regeneration of the outgoing signals. Like with the previous devices, wavelength-selectivity of the Light-Valves and Reflectors enables increased performance.

<u>SWASP LEDs and LASERs</u>

The original functionality sought and envisaged for the device of the present disclosure, involved photo-detection, that is, absorption of photons. However, through particular choices of parameters, the same device concept can also become and photon-emitter, a Light Emitting Device (LED). When appropriately positioned in a microcavity, there is no obvious reason for the emitted light not to be coherent, and therefore for this device to function as a LASER.

One more and very important advantage of Inter Subband Transitions, is the cancellation of some materials-specific parameters determining the probability of any giver transition to occur. Such is the case with band-gap magnitude and type, direct or indirect. Actually, this property of Inter Subband Transitions is extremely appealing to make devices made with materials systems, such as Si and Ge.

Quantum Cascade LASERs have demonstrated the feasibility of such physical mechanisms. However, there are several fundamental differences between SWASP and Quantum Cascade mechanisms. They are both unipolar, and rely on inter subband transitions.

In Quantum Cascade LASERs carriers are forced through the sequence of potential barriers that create the quantization effects (the subbands). The carriers go from a subband in a QW, tunnel trough the potential barrier, and fall into the subband of the next QW, and in the process emits a photon to compensate the loss of potential energy. Carriers are forced through the heterojunction layers by an externally applied field perpendicular to the direction of the heterojunction epitaxial growth.

In SWASP devices, the carriers will not tunnel through the QW barriers, because they are too wide to allow tunnel, and because there is no electric field across them. This preserves the "ideal" shape of the potential well, as defined by the heterojunction epitaxial growth. With the structure of the invention, the electric fields, built-in or externally applied, are between the lateral contacts and therefore always parallel to the plane of the QW.

With the SWASP structure, the transitions take place between two distinct eigenvalues of the same QW, within the same quantum confinement barriers. This contrasts with the transitions between two ground states of consecutive QWs, where one eigenvalue becomes a lower energy level than he other, by the action of the aforementioned electric field.

Some of the considerations leading to the optimized design for photo-detection are the same for photo-emission: choice of transitions favored by quantum mechanical selection rules, high spectral purity, energy bands with very light charge carriers, etc.

The insertion of a SWASP Quantum Well in a microcavity, should enable the emission of coherent light, that is, the SWASP device would become a LASER. The operation of the SWASP-based LASER can be either by photoluminescence or by electroluminescence.

Ideally, the workfunction of the metal injecting carriers into the high-energy eigenstate, should have a higher potential energy than that eigenstate itself, and therefore, very little voltage would be required to operate the device. Ideally, it should also happen that the band edge of the "contact insulator" should be on a lower potential energy level than the workfunction.

For carrier injection, both the high and the low eigenstates should be below the band edges of the "contact insulators" of both sides. These could be made with the same material.

The problem is that the largest workfunction listed for metals, is not sufficiently large to for this scheme to work with photons in the visible range, for the valence band of Si or Ge. For photons in the visible range, it seems inevitable that a fairly high voltage would need to the applied in order to enable tunneling currents to be injected through one of the contact

insulators, at one of the lateral contacts. This is no longer necessary, if the eigenvalue which carriers need to be injected into, is below the metal workfunction of the metal contact.

SWASP with "Heterojunction Integrated Thermionic Cooler" (HIT)

The architecture of the SWASP device layers, is fabricated with a process flow for "Vertical Devices", where the fundamental active regions and critical dimensions are atomically controlled during low temperature heteroepitaxial deposition. In this feature resides a fundamental difference and advantage over "Planar Devices", which are the "standard technology".

There is yet another compelling argument favoring the device architecture here disclosed, and which is related to the effortless and straightforward heteroepitaxial deposition of films that just add more features and advantages, without placing any serious drawbacks or limitations, processing or functionality wise.

Recently, it has been shown that certain heterostructures, with a bias applied thereto, have the capability of lowering the temperature in adjacent materials. These devices and structures have been designated as "Heterojunction Integrated Thermionic Coolers", and seem to present no problem for their implementation in silicon-compatible materials, and in particular to be inserted at one or more positions in the SWASP device. It is especially attractive the possibility of cooling down (with respect to Room Temperature) the portion of the SWASP dedicated to IR and FIR detection, because of the closeness of the energies involved with respect to the value of thermal noise (K_BT). Therefore, locally lowering the temperature (T), should enable a much improved signal-to-noise ratio of the IR and FIR signal detection.

The Band-Gap Engineering required to achieve this kind of functionality, is definitely out of question for "standard technology", and seems and absolute natural fit with the SWASP device and process architecture.

SWASP devices with of Amorphous or Poly Active Layers

As already mentioned herein, the SWASP concept of the invention can be implemented in any materials system. The examples given have used the silicon-compatible materials, due to the obvious economic interest in implementing the device in that system.

The examples given, always called for epitaxial pseudomorphic growth to insure high crystalline quality of all the active layers in the device. Naturally such kind of layers can offer the highest performance in terms of defect density, recombination rates, charge carrier mobility, etc.

However, pseudomorphic growth of such heterojunctions demands extreme control of the processing conditions, and naturally requires high quality substrates, that is single crystal silicon wafers.

Low cost, "large area" substrates and processing, is only possible with amorphous or poly-crystalline films, and therefore some modifications are needed to the structures defined single-crystal version of the device. As some of the band-gap engineering with silicon alloys, actually requires strained layers, it becomes impossible to simple mimic the layer sequence and obtain the same band alignments with the amorphous/poly version of the same films.

Some types of band alignments and/or some ranges of band offsets won't easy if possible at all, with the same kinds of silicon-based alloys. Other materials, or less degrees of freedom in design the structures would have to be accepted.

Claims

1. An opto-electronic device, comprising a substrate (10), a number of different wavelength-selective active layers (12) arranged in a vertical stack such that the incident light is caused to travel through layers with monotonically decreasing band-gaps, said active layers being wavelength-selective photon-absorbing layers and/or photon-emitting layers, whereby photons of different energies are selectively absorbed in or emitted by said active layers, and contact means (17, 18) arranged for extracting charge carriers generated in the photon-absorbing layers and/or injecting charge carriers into the photon-emitting layers.

2. A device as claimed in claim 1, wherein the stack of layers includes a wide band-gap insulator layer (14) positioned underneath each active layer (16) and on top of the upper layer.

3. A device as claimed in claim 1 or 2, wherein the active layers (16) are dimensioned to adjust the quantum well depth, thereby to create absorbing/emitting properties for the layers, that are independent from the color wavelength.

4. A device as claimed in claim 1 or 2, wherein the active layers have an alloy composition chosen such that the absorbing/emitting properties thereof are independent from the wavelength.

5. A device as claimed in either of the preceding claims, wherein the contact means are implemented through lateral contacts made separately to each of said active layer or set of active layers having the same parameters.

6. A device as claimed in claim 5, wherein said contacts are adapted such that the electrons and the holes are extracted separately from the photon-absorbing layers or injected separately into the photon-emitting layers.

7. A device as claimed in claim 6, wherein said contacts are formed with Metal-Insulator-Semiconductor (MIS) or Metal-Oxide-Semiconductor (MOS) systems using iltra-thin insulator/oxide films.

8. A device as claimed in either of the preceding claims, wherein all the active layers are adapted to be Quantum Wells, whereby said active layers have an adjustable absorption and/or emission edge.

9. A device as claimed in claim 8, wherein all the active layers are adjusted to be capable of being transparent to visible light.

10. A device as claimed in either of the preceding claims, adapted to serve as a Solar Cell device and/or an Imager and/or a Light Valve.

11. A device as claimed in either of the claims 1 to 9, adapted to produce coherent light.

PRIOR ART

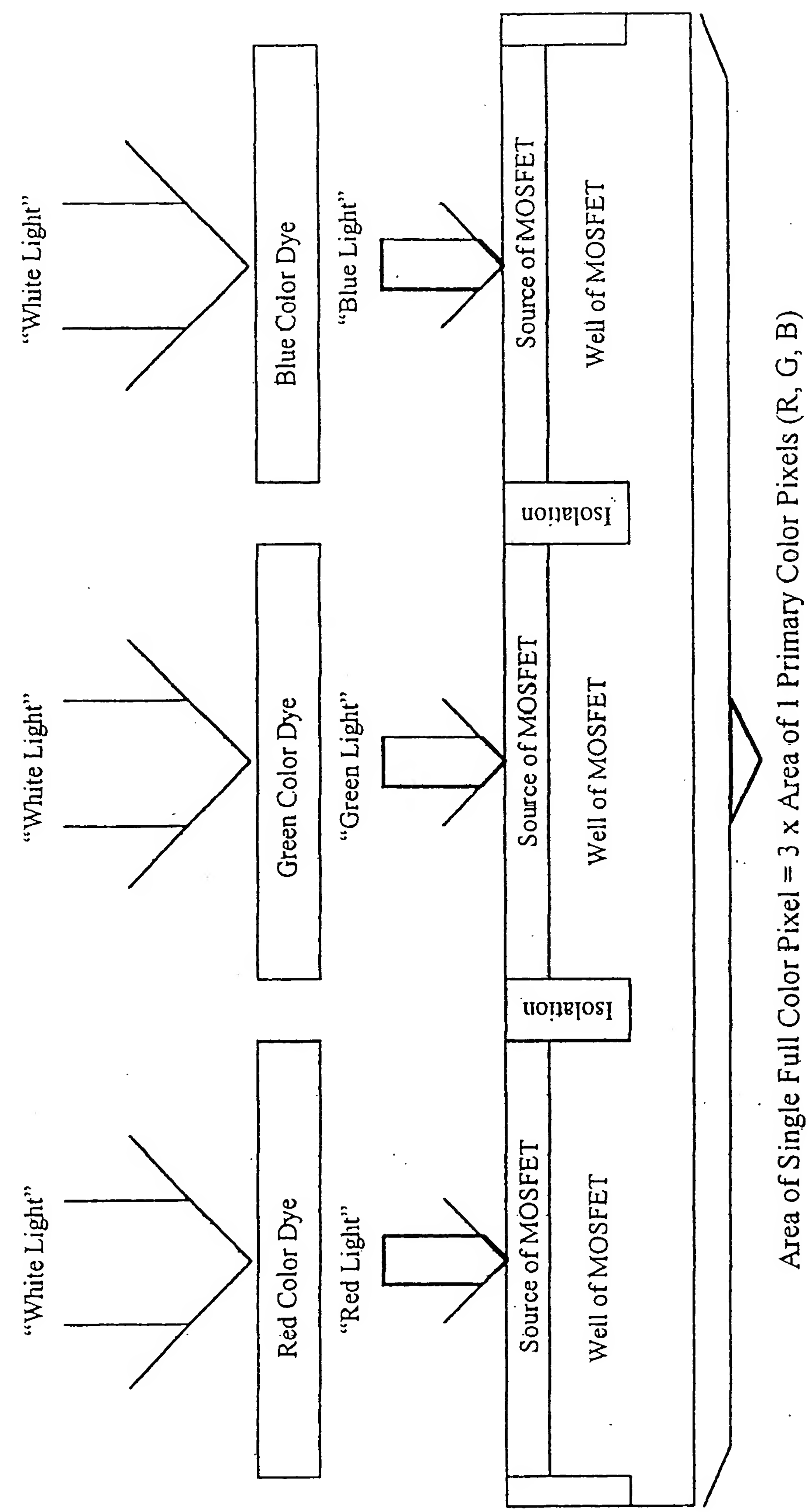


Figure 1

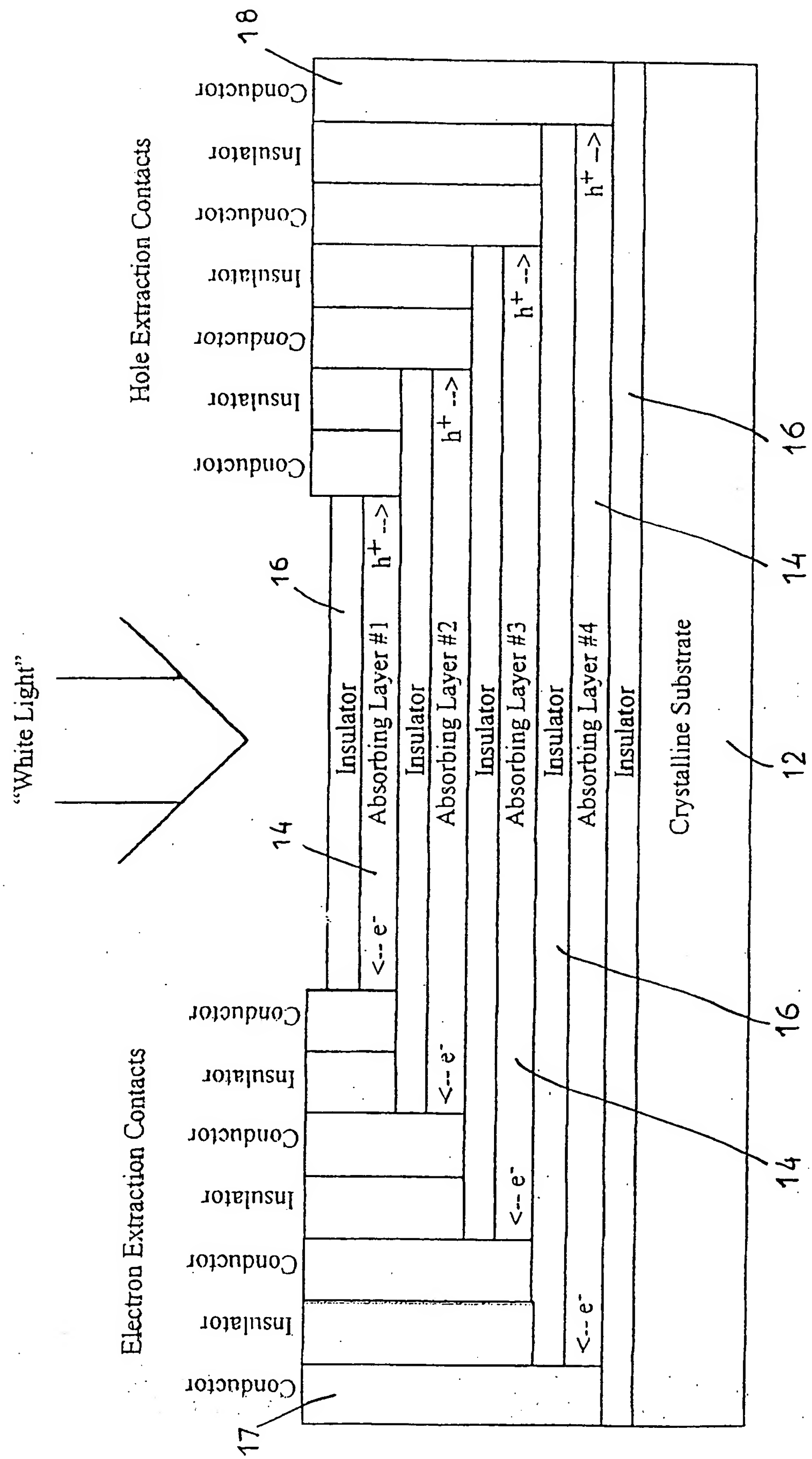

Hole Extraction Contacts
Electron Extraction Contacts
"White Light"
Conductor
Insulator
Conductor
Insulator
Conductor
Insulator
Conductor
Insulator
Absorbing Layer #1
Insulator
Absorbing Layer #2
Insulator
Absorbing Layer #3
Insulator
Absorbing Layer #4
Insulator
Crystalline Substrate
h+ -->
<-- e-
18
16
14
12
17

Figure 2

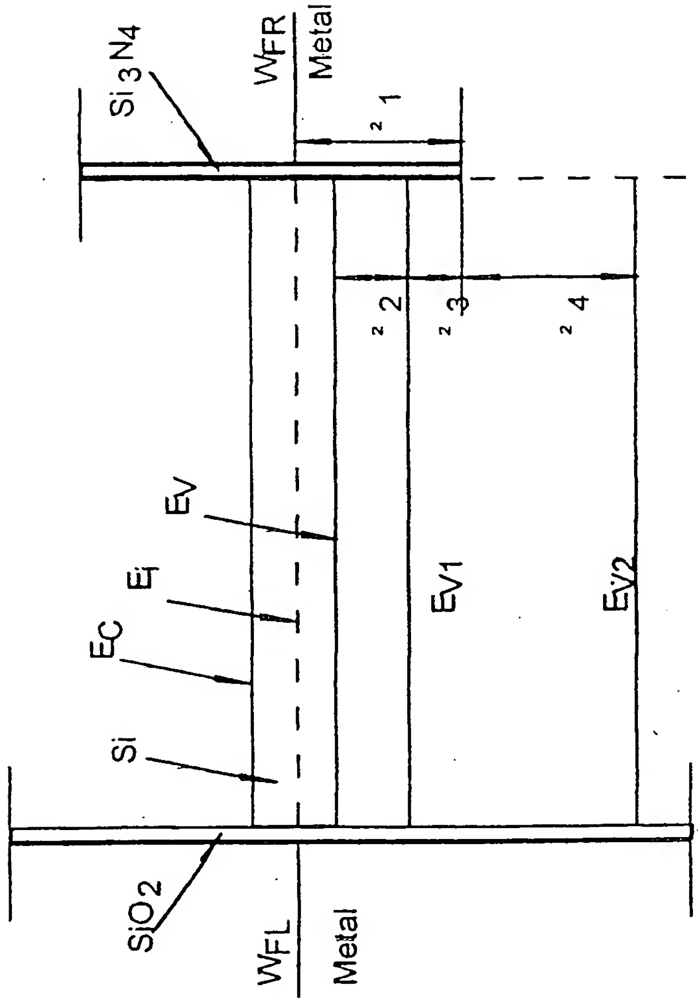


Figure 3

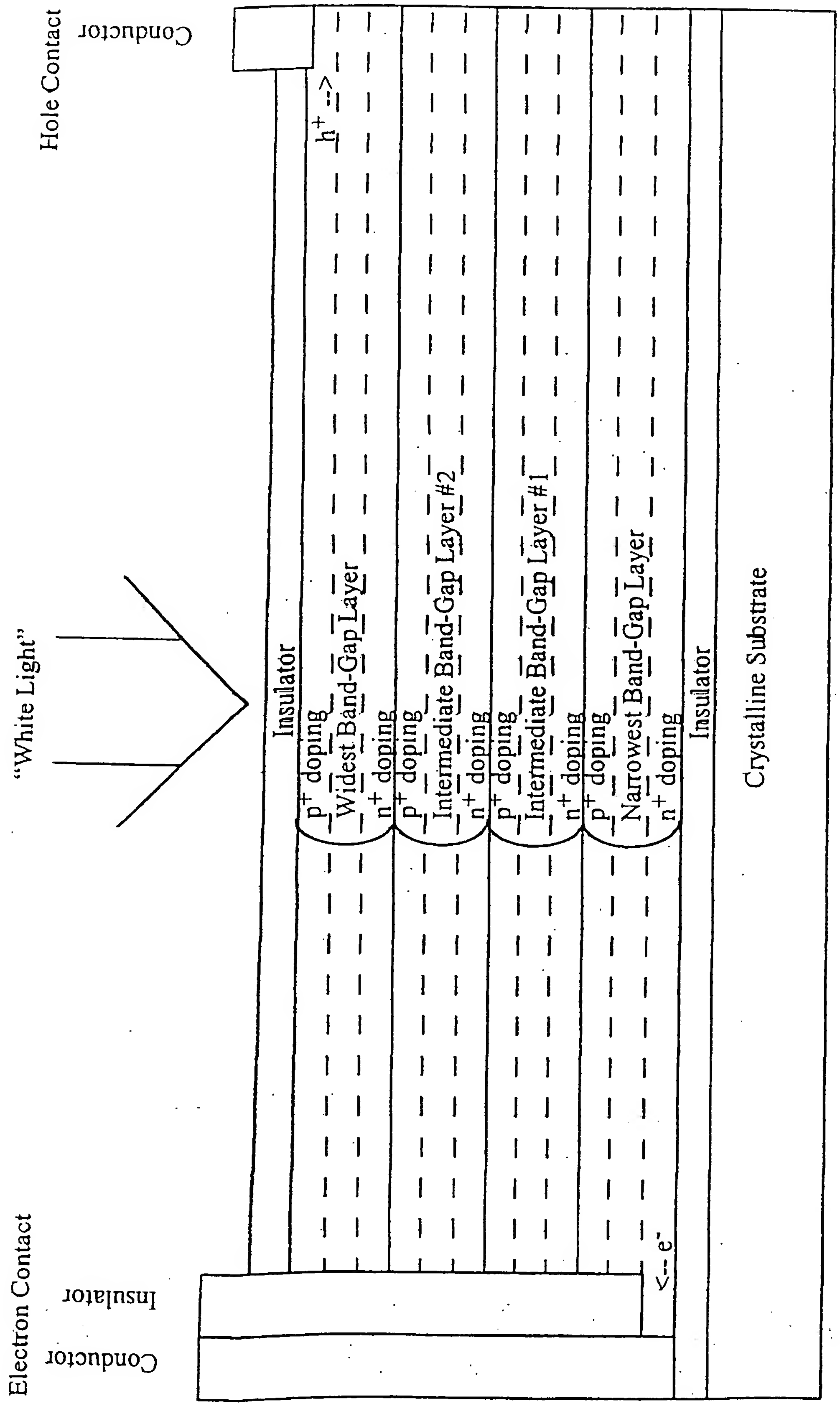

Hole Contact
Conductor
"White Light"
Insulator
h^+ -->
p^+ doping
Widest Band-Gap Layer
n^+ doping
p^+ doping
Intermediate Band-Gap Layer #2
n^+ doping
p^+ doping
Intermediate Band-Gap Layer #1
n^+ doping
p^+ doping
Narrowest Band-Gap Layer
n^+ doping
<-- e^-
Insulator
Crystalline Substrate
Electron Contact
Insulator
Conductor

Figure 4

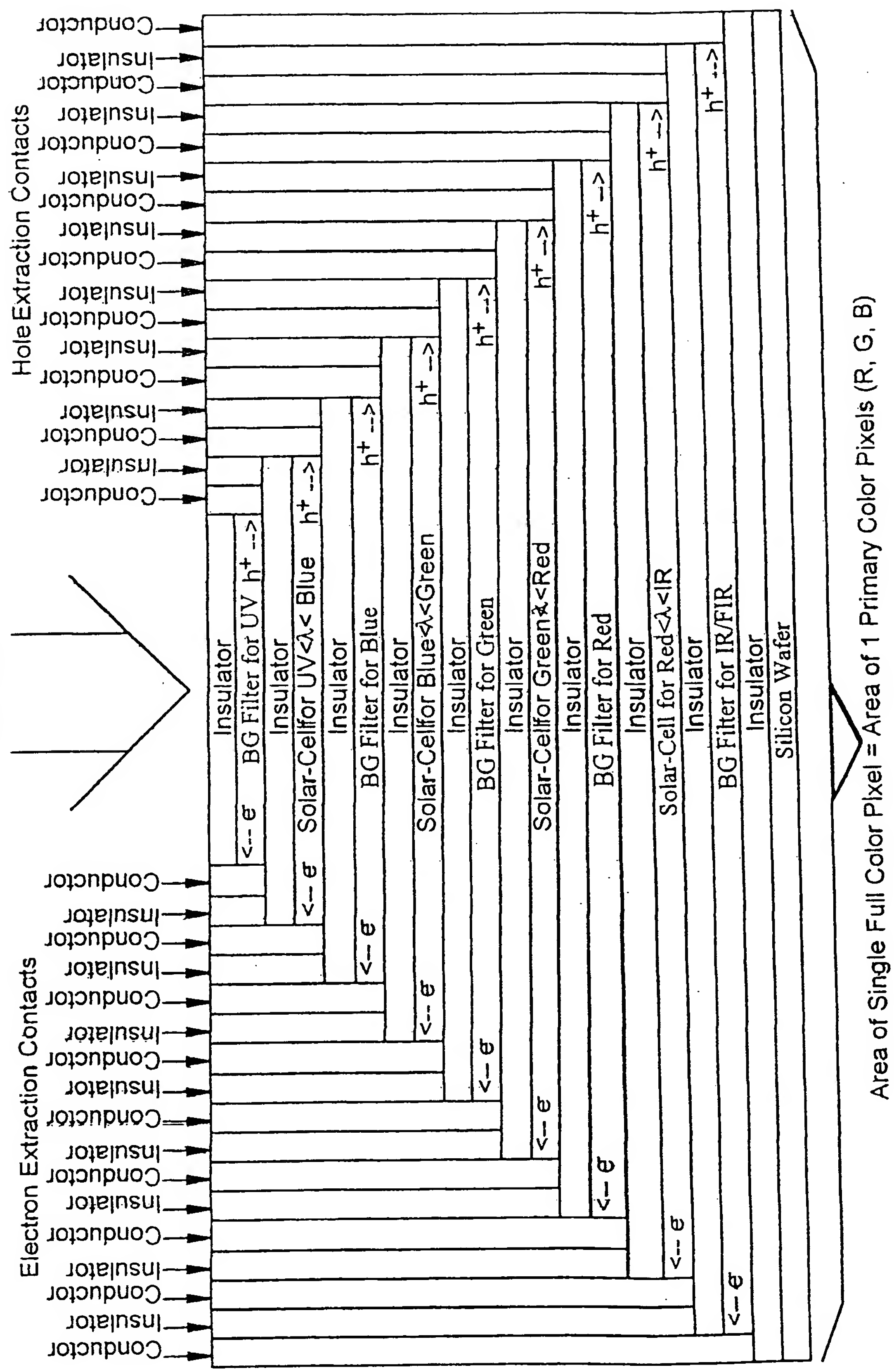

"White Light"
Hole Extraction Contacts
Electron Extraction Contacts
Conductor
Insulator
Insulator
BG Filter for UV
Solar-Cellfor UV<λ< Blue
BG Filter for Blue
Solar-Cellfor Blue<λ<Green
BG Filter for Green
Solar-Cellfor Green<λ<Red
BG Filter for Red
Solar-Cell for Red<λ<IR
BG Filter for IR/FIR
Silicon Wafer
h^+ -->
<-- e
Area of Single Full Color Pixel = Area of 1 Primary Color Pixels (R, G, B)

Figure 5A

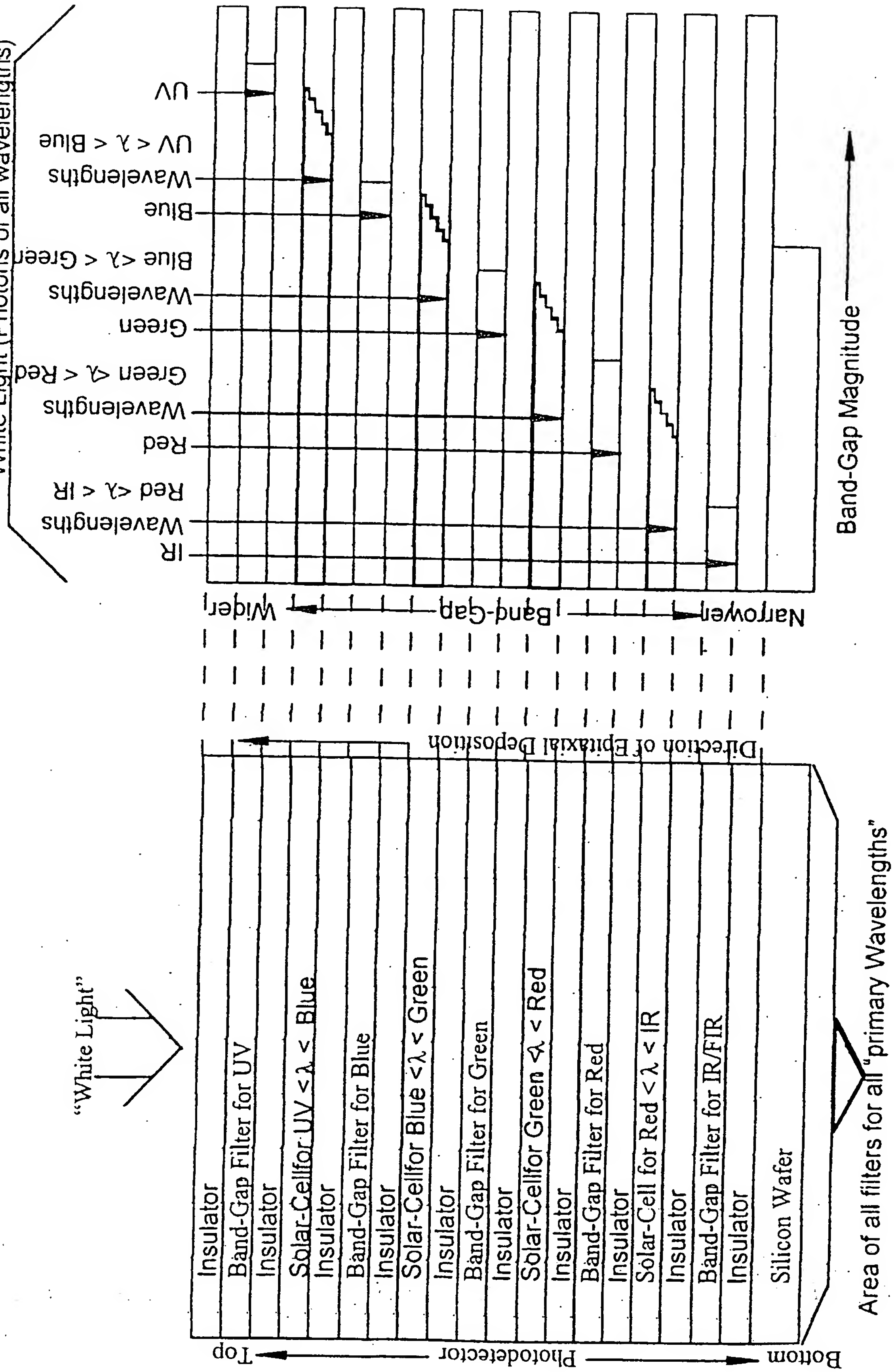

White Light (Photons of all wavelengths)
UV
UV < λ < Blue
Wavelengths
Blue
Blue <λ < Green
Wavelengths
Green
Green <λ < Red
Wavelengths
Red
Red <λ < IR
Wavelengths
IR
Band-Gap Magnitude
Wider
Band-Gap
Narrower
Direction of Epitaxial Deposition
"White Light"
Insulator
Band-Gap Filter for UV
Insulator
Solar-Cellfor UV < λ < Blue
Insulator
Band-Gap Filter for Blue
Insulator
Solar-Cellfor Blue <λ < Green
Insulator
Band-Gap Filter for Green
Insulator
Solar-Cellfor Green <λ < Red
Insulator
Band-Gap Filter for Red
Insulator
Solar-Cell for Red < λ < IR
Insulator
Band-Gap Filter for IR/FIR
Insulator
Silicon Wafer
Area of all filters for all "primary Wavelengths"
Top
Photodetector
Bottom

Figure 5B

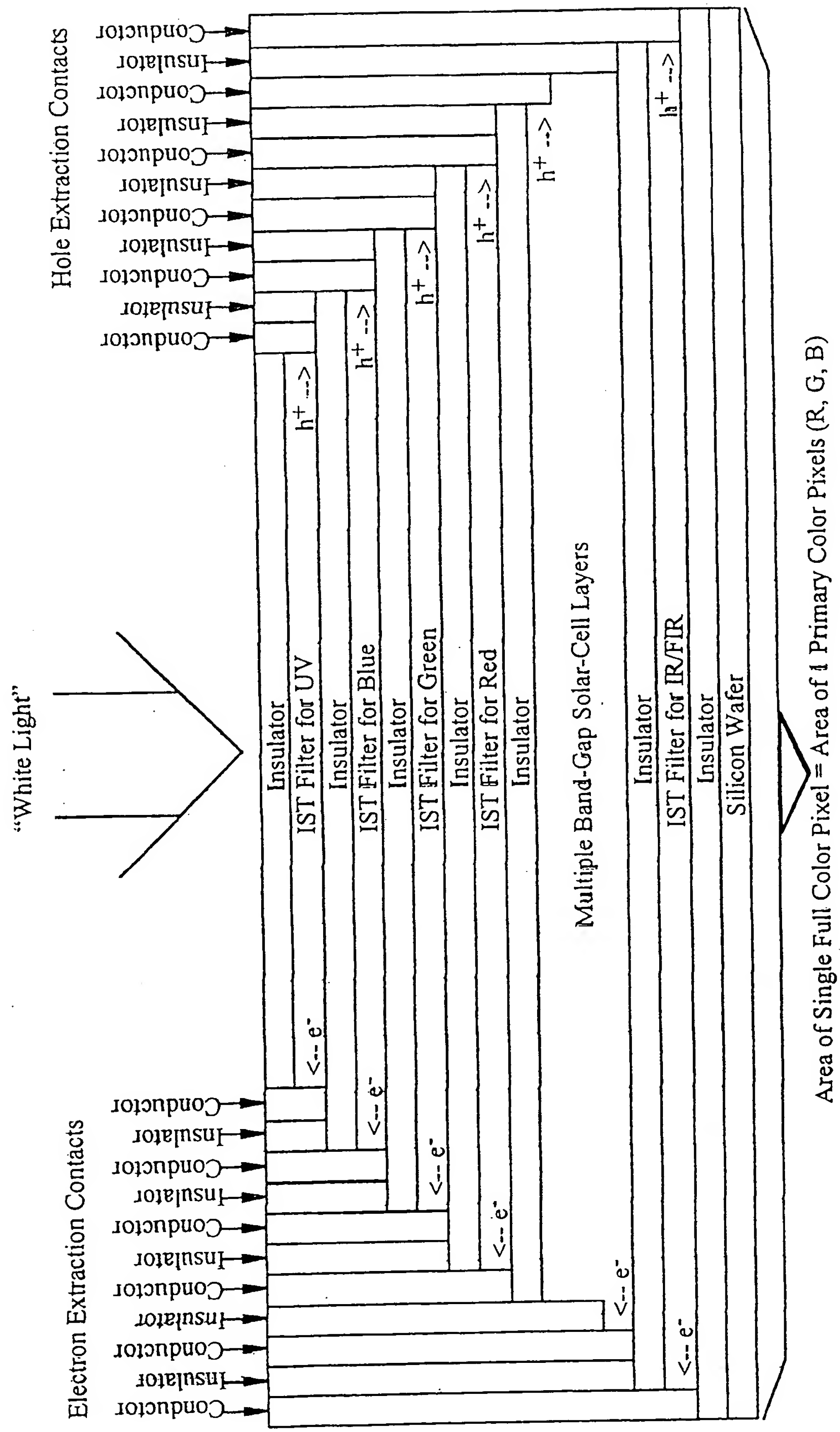

"White Light"
Hole Extraction Contacts
Electron Extraction Contacts
Conductor
Insulator
Insulator
IST Filter for UV
Insulator
IST Filter for Blue
Insulator
IST Filter for Green
Insulator
IST Filter for Red
Insulator
Multiple Band-Gap Solar-Cell Layers
Insulator
IST Filter for IR/FIR
Insulator
Silicon Wafer
h+ -->
<-- e-
Area of Single Full Color Pixel = Area of 1 Primary Color Pixels (R, G, B)

Figure 6A

Figure 6B

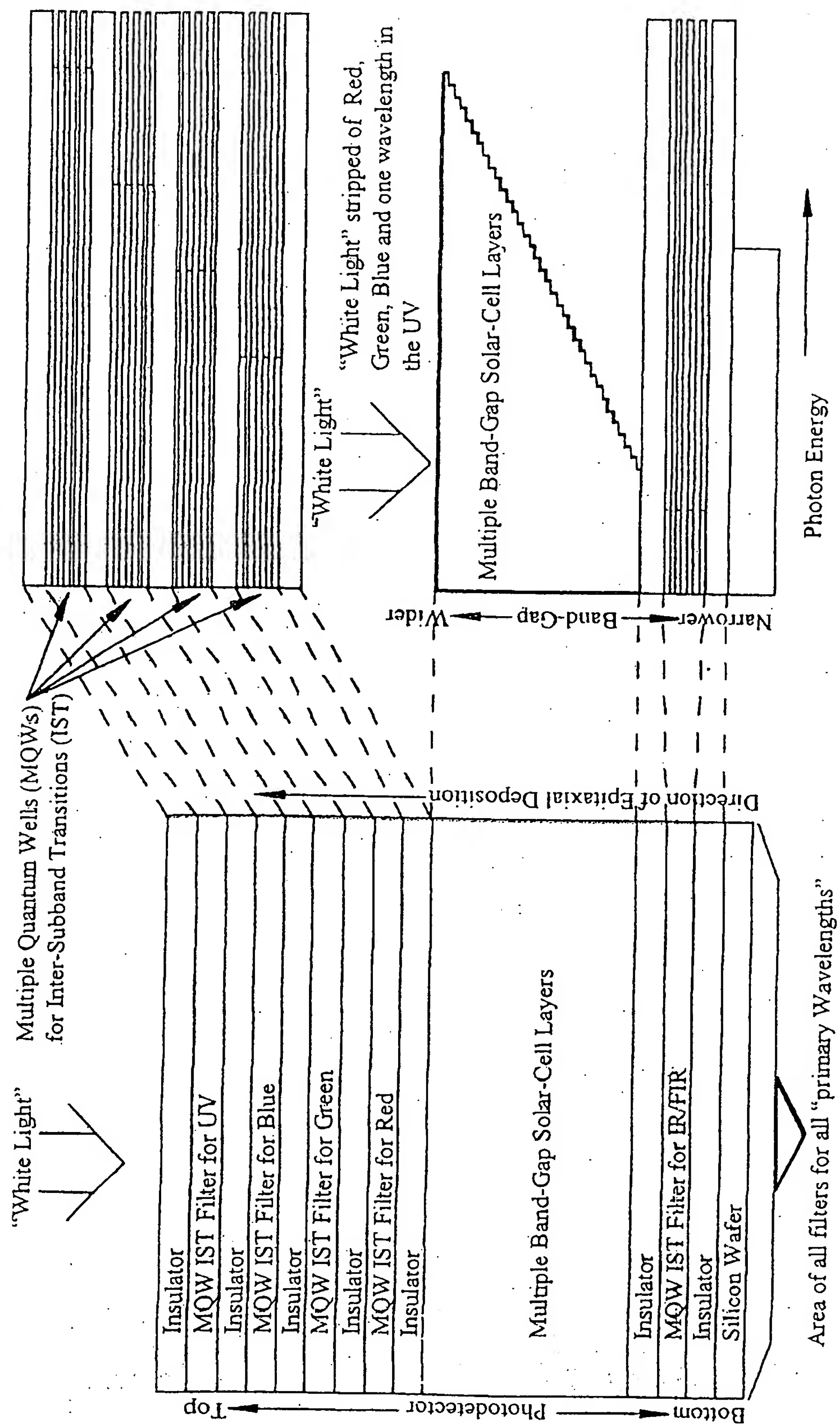

"White Light"
Multiple Quantum Wells (MQWs)
for Inter-Subband Transitions (IST)
Insulator
MQW IST Filter for UV
Insulator
MQW IST Filter for Blue
Insulator
MQW IST Filter for Green
Insulator
MQW IST Filter for Red
Insulator
Multiple Band-Gap Solar-Cell Layers
Insulator
MQW IST Filter for IR/FIR
Insulator
Silicon Wafer
Area of all filters for all "primary Wavelengths"
Top
Photodetector
Bottom
Direction of Epitaxial Deposition
Wider
Band-Gap
Narrower
"White Light"
"White Light" stripped of Red, Green, Blue and one wavelength in the UV
Multiple Band-Gap Solar-Cell Layers
Photon Energy

Figure 7

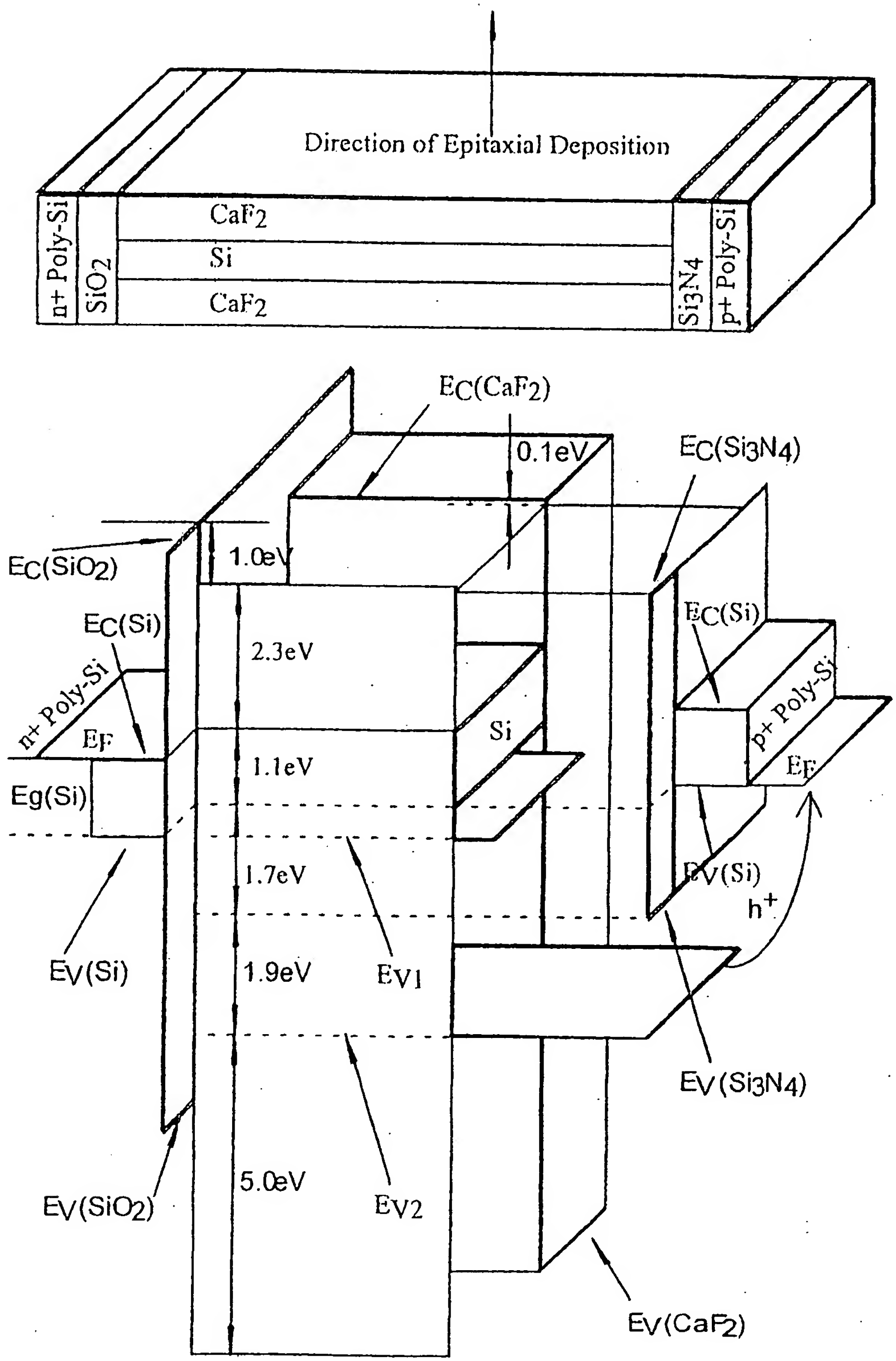

Direction of Epitaxial Deposition
n+ Poly-Si
SiO2
CaF2
Si
CaF2
Si3N4
p+ Poly-Si
EC(CaF2)
0.1eV
EC(Si3N4)
EC(SiO2)
1.0eV
EC(Si)
2.3eV
n+ Poly-Si
EF
Si
EC(Si)
p+ Poly-Si
EF
1.1eV
Eg(Si)
1.7eV
EV(Si)
h+
EV(Si)
1.9eV
EV1
EV(Si3N4)
5.0eV
EV(SiO2)
EV2
EV(CaF2)

Figure 8A

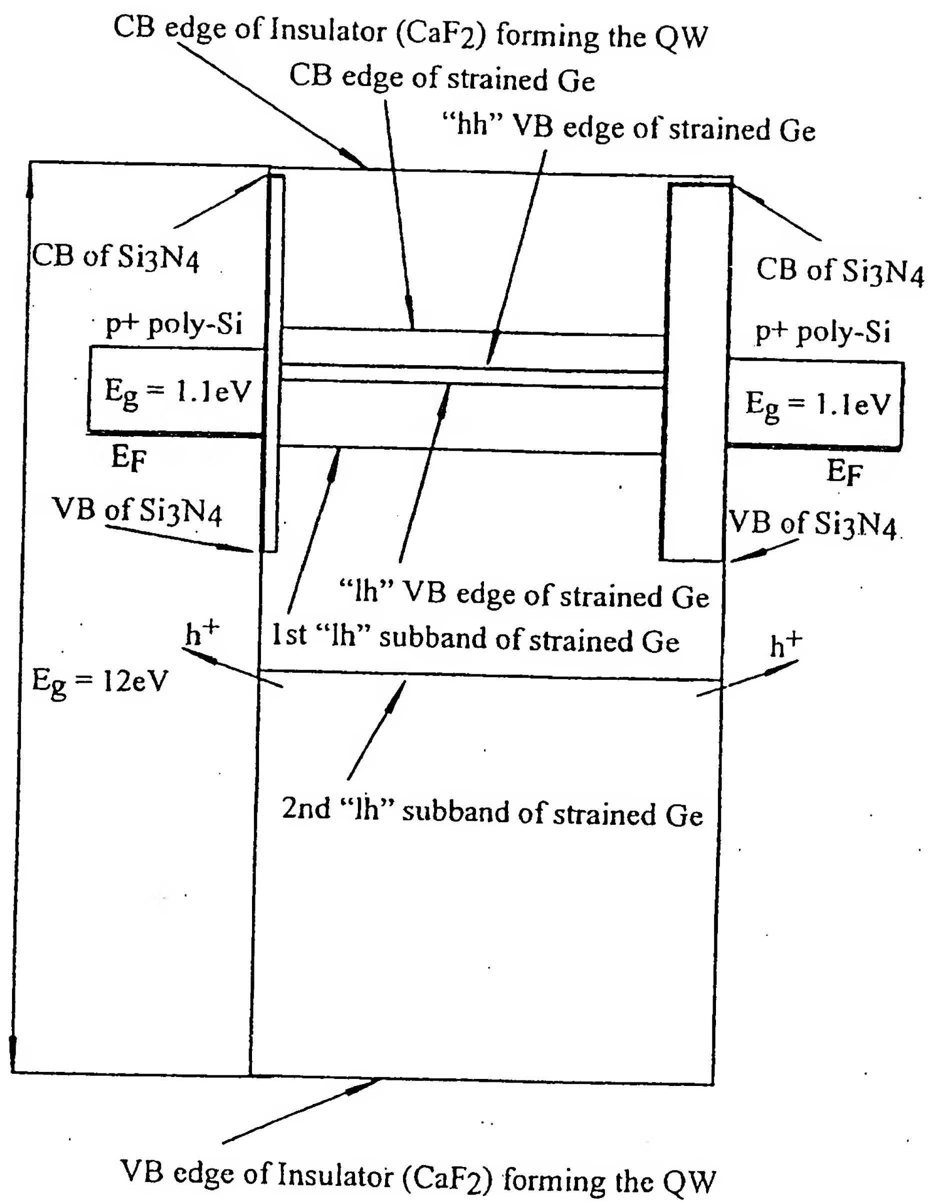

CB edge of Insulator (CaF_2) forming the QW
CB edge of strained Ge
"hh" VB edge of strained Ge
CB of Si_3N_4
CB of Si_3N_4
p+ poly-Si
p+ poly-Si
E_g = 1.1eV
E_g = 1.1eV
E_F
E_F
VB of Si_3N_4
VB of Si_3N_4
"lh" VB edge of strained Ge
1st "lh" subband of strained Ge
h^+
h^+
E_g = 12eV
2nd "lh" subband of strained Ge
VB edge of Insulator (CaF_2) forming the QW

Figure 8B

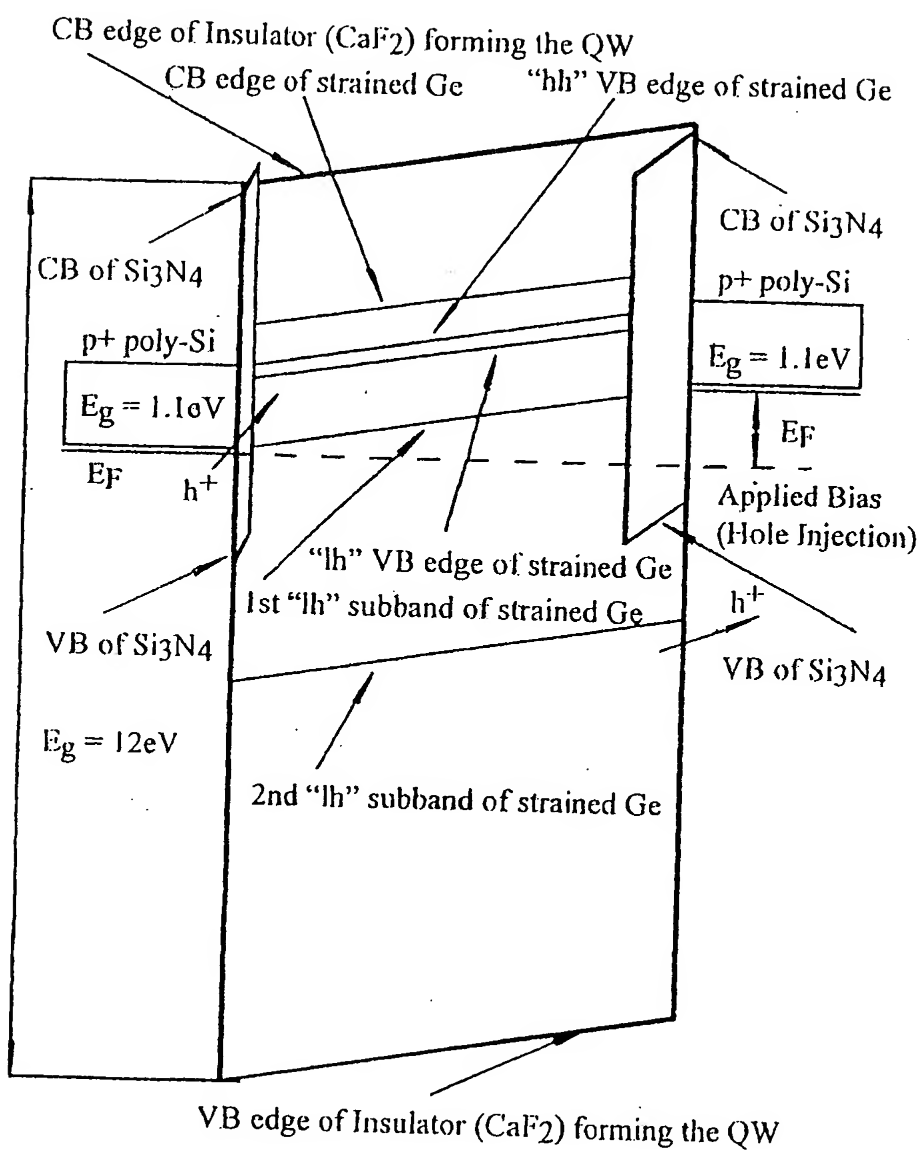

CB edge of Insulator (CaF_2) forming the QW
CB edge of strained Ge
"hh" VB edge of strained Ge
CB of Si_3N_4
CB of Si_3N_4
p+ poly-Si
p+ poly-Si
E_g = 1.1eV
E_g = 1.1eV
E_F
E_F
h^+
Applied Bias
(Hole Injection)
"lh" VB edge of strained Ge
1st "lh" subband of strained Ge
h^+
VB of Si_3N_4
VB of Si_3N_4
E_g = 12eV
2nd "lh" subband of strained Ge
VB edge of Insulator (CaF_2) forming the QW

Figure 8C

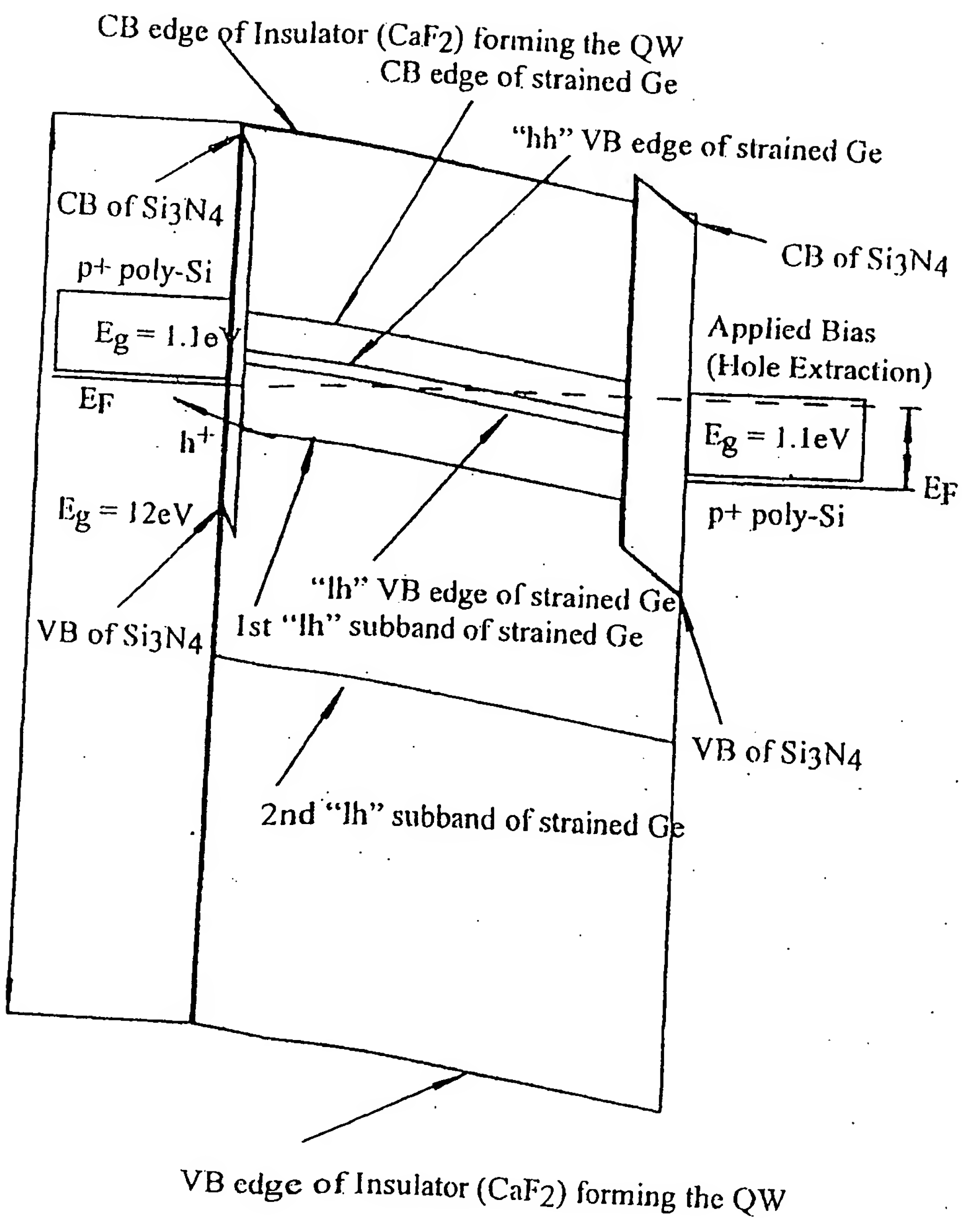

CB edge of Insulator (CaF_2) forming the QW
CB edge of strained Ge
"hh" VB edge of strained Ge
CB of Si_3N_4
p+ poly-Si
E_g = 1.1eV
E_F
h^+
E_g = 12eV
VB of Si_3N_4
CB of Si_3N_4
Applied Bias
(Hole Extraction)
E_g = 1.1eV
E_F
p+ poly-Si
"lh" VB edge of strained Ge
1st "lh" subband of strained Ge
VB of Si_3N_4
2nd "lh" subband of strained Ge
VB edge of Insulator (CaF_2) forming the QW

Figure 9A

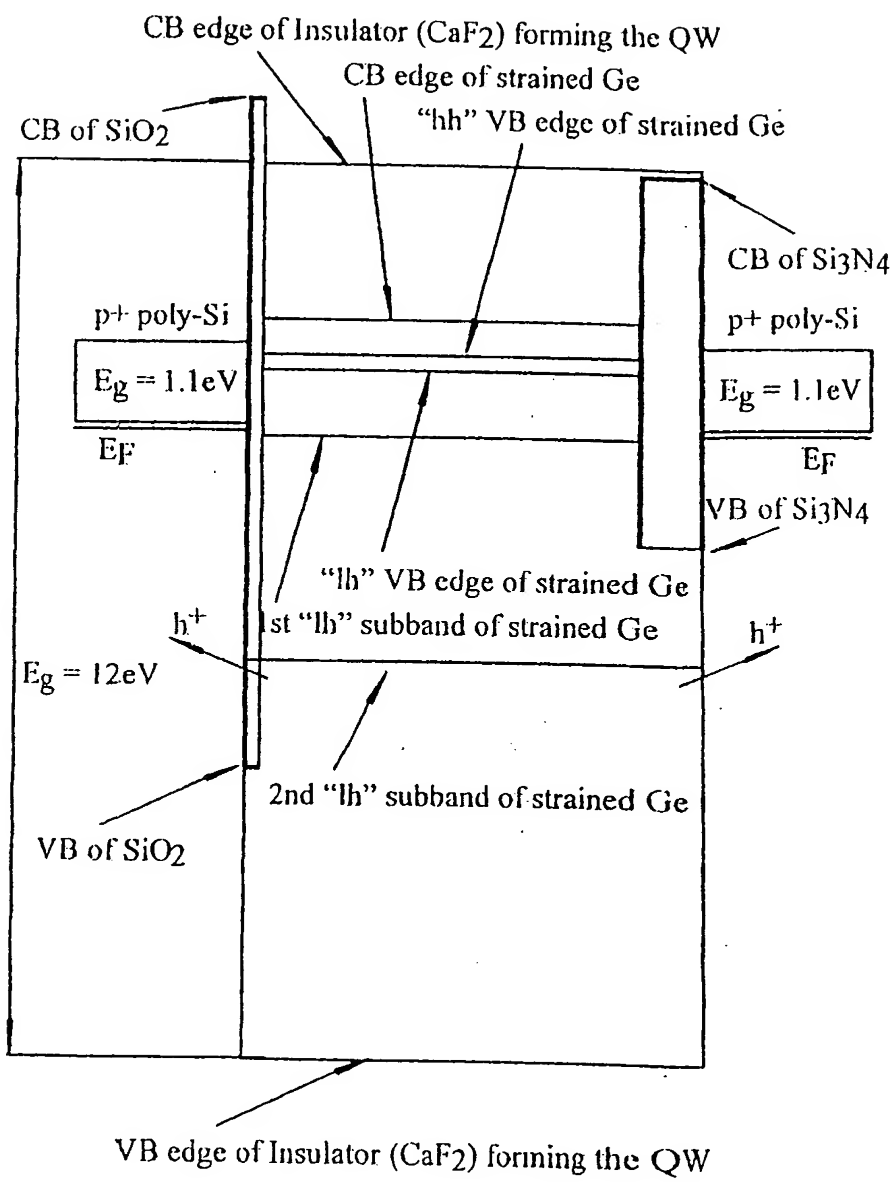

CB edge of Insulator (CaF2) forming the QW
CB edge of strained Ge
"hh" VB edge of strained Ge
CB of SiO2
CB of Si3N4
p+ poly-Si
Eg = 1.1eV
EF
p+ poly-Si
Eg = 1.1eV
EF
VB of Si3N4
"lh" VB edge of strained Ge
1st "lh" subband of strained Ge
h+
h+
Eg = 12eV
2nd "lh" subband of strained Ge
VB of SiO2
VB edge of Insulator (CaF2) forming the QW

Figure 9B

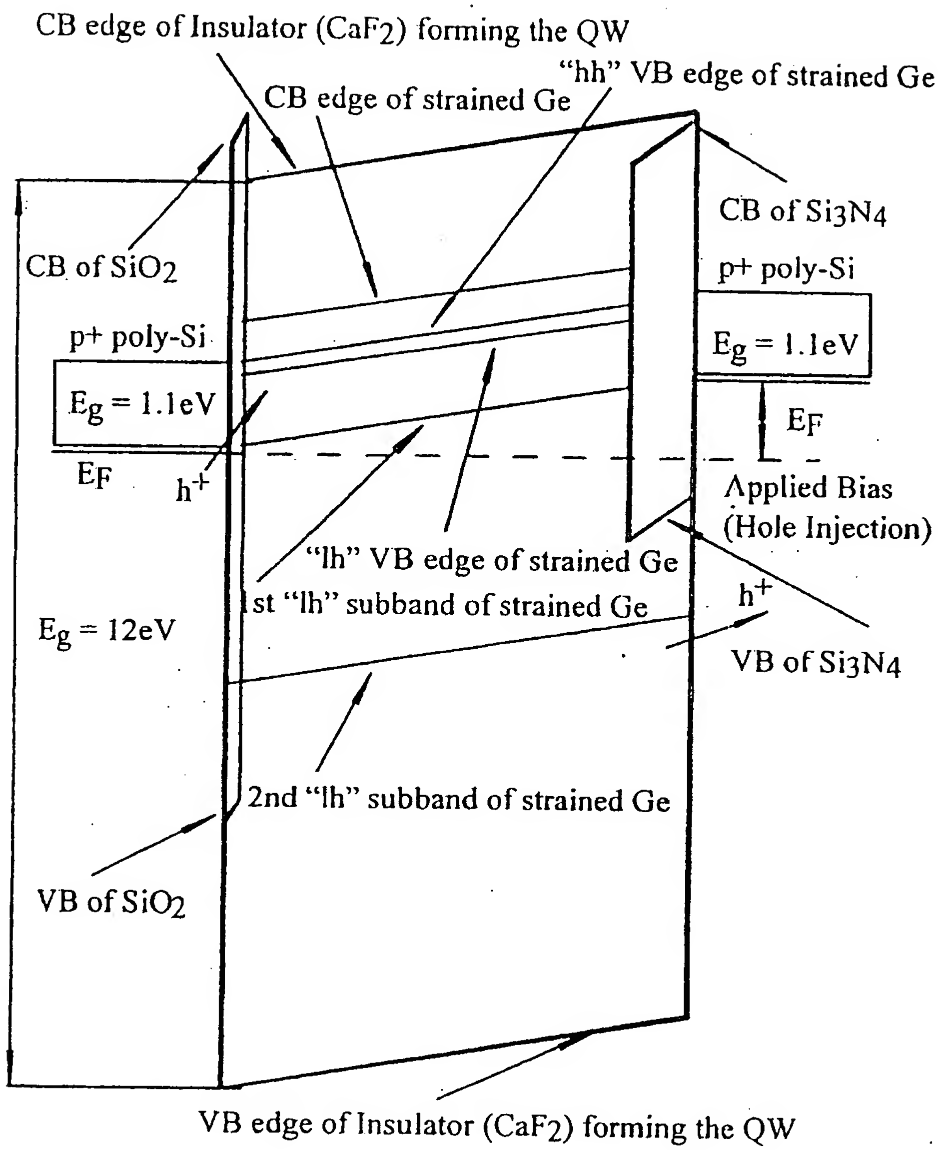
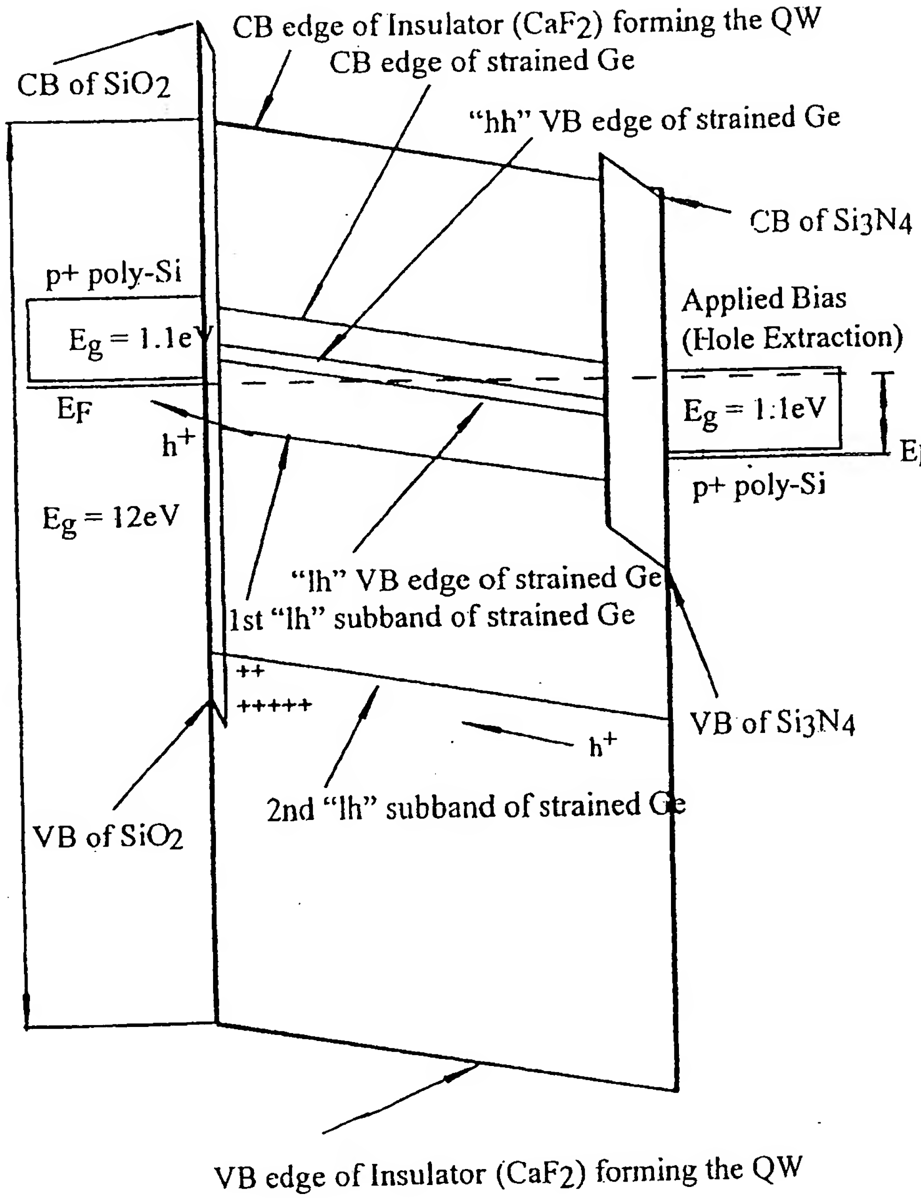

CB edge of Insulator (CaF_2) forming the QW
"hh" VB edge of strained Ge
CB edge of strained Ge
CB of Si_3N_4
p+ poly-Si
E_g = 1.1eV
CB of SiO_2
p+ poly-Si
E_g = 1.1eV
E_F
E_F
h^+
Applied Bias
(Hole Injection)
"lh" VB edge of strained Ge
1st "lh" subband of strained Ge
h^+
E_g = 12eV
VB of Si_3N_4
2nd "lh" subband of strained Ge
VB of SiO_2
VB edge of Insulator (CaF_2) forming the QW

Figure 9C


CB edge of Insulator (CaF_2) forming the QW
CB edge of strained Ge
CB of SiO_2
"hh" VB edge of strained Ge
CB of Si_3N_4
p+ poly-Si
Applied Bias
(Hole Extraction)
E_g = 1.1eV
E_F
h^+
E_g = 1.1eV
E_F
p+ poly-Si
E_g = 12eV
"lh" VB edge of strained Ge
1st "lh" subband of strained Ge
++
+++++
VB of Si_3N_4
h^+
2nd "lh" subband of strained Ge
VB of SiO_2
VB edge of Insulator (CaF_2) forming the QW

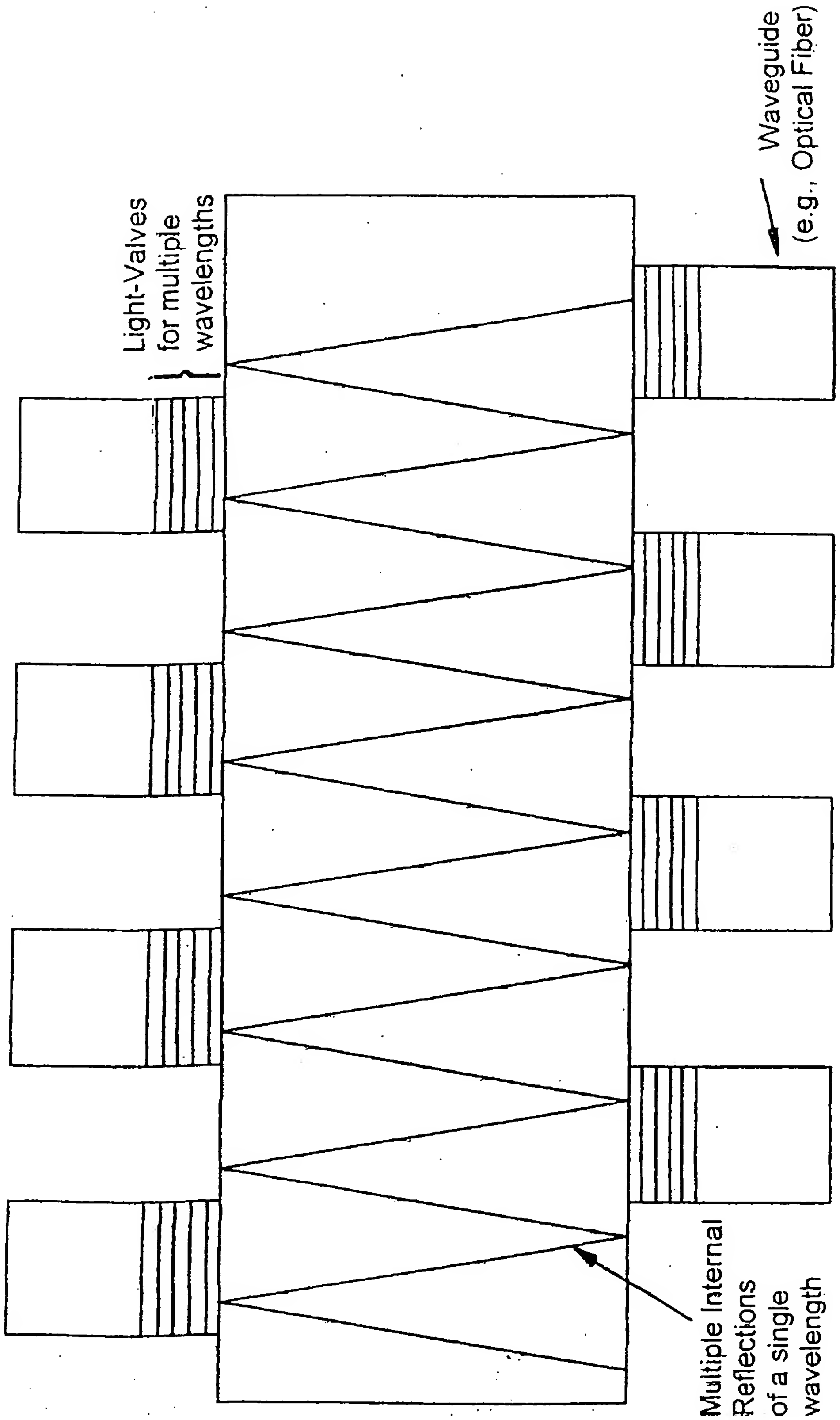

Waveguide
(e.g., Optical Fiber)
Light-Valves
for multiple
wavelengths
Multiple Internal
Reflections
of a single
wavelength

Figure 10

INTERNATIONAL SEARCH REPORT

International Application No
PCT/EP 00/05590

A. CLASSIFICATION OF SUBJECT MATTER
IPC 7 H01L31/0352 H01L31/11

According to International Patent Classification (IPC) or to both national classification and IPC

B. FIELDS SEARCHED

Minimum documentation searched (classification system followed by classification symbols)
IPC 7 H01L G02F

Documentation searched other than minimum documentation to the extent that such documents are included in the fields searched

Electronic data base consulted during the international search (name of data base and, where practical, search terms used)

EPO-Internal, WPI Data, PAJ, INSPEC

C. DOCUMENTS CONSIDERED TO BE RELEVANT

Category °	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
X	US 5 689 123 A (WELCH DAVID F ET AL) 18 November 1997 (1997-11-18) column 16, line 29 -column 18, line 42 figure 11	1,3-10
X	US 4 975 567 A (BISHOP STEPHEN G ET AL) 4 December 1990 (1990-12-04) column 1, line 15 - line 53 column 2, line 59 -column 5, line 49	1-4
Y		10
Y	US 4 705 361 A (REED MARK A ET AL) 10 November 1987 (1987-11-10) column 3, line 41 -column 7, line 64 figures 2-8	10

-/--

[X] Further documents are listed in the continuation of box C.

[X] Patent family members are listed in annex.

° Special categories of cited documents :

"A" document defining the general state of the art which is not considered to be of particular relevance

"E" earlier document but published on or after the international filing date

"L" document which may throw doubts on priority claim(s) or which is cited to establish the publication date of another citation or other special reason (as specified)

"O" document referring to an oral disclosure, use, exhibition or other means

"P" document published prior to the international filing date but later than the priority date claimed

"T" later document published after the international filing date or priority date and not in conflict with the application but cited to understand the principle or theory underlying the invention

"X" document of particular relevance; the claimed invention cannot be considered novel or cannot be considered to involve an inventive step when the document is taken alone

"Y" document of particular relevance; the claimed invention cannot be considered to involve an inventive step when the document is combined with one or more other such documents, such combination being obvious to a person skilled in the art.

"&" document member of the same patent family

Date of the actual completion of the international search	Date of mailing of the international search report
25 October 2000	06.11.00

Name and mailing address of the ISA	Authorized officer
European Patent Office, P.B. 5818 Patentlaan 2 NL – 2280 HV Rijswijk Tel. (+31–70) 340–2040, Tx. 31 651 epo nl,	Visscher, E

International Application No
PCT/EP 00/05590

C.(Continuation) DOCUMENTS CONSIDERED TO BE RELEVANT

Category °	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
A	US 5 646 421 A (LIU HUI CHUN) 8 July 1997 (1997-07-08) column 2, line 34 - line 58 column 3, line 4 - line 7 column 3, line 37 -column 4, line 42	1-10
A	EP 0 812 023 A (MAX PLANCK GESELLSCHAFT) 10 December 1997 (1997-12-10) column 8, line 9 -column 9, line 39 column 10, line 42 -column 11, line 31 figures 2,4	1-10

International application No.
PCT/EP 00/05590

INTERNATIONAL SEARCH REPORT

Box I Observations where certain claims were found unsearchable (Continuation of item 1 of first sheet)

This International Search Report has not been established in respect of certain claims under Article 17(2)(a) for the following reasons:

1. ☐ Claims Nos.:
because they relate to subject matter not required to be searched by this Authority, namely:

2. ☒ Claims Nos.: 11
because they relate to parts of the International Application that do not comply with the prescribed requirements to such an extent that no meaningful International Search can be carried out, specifically:
see FURTHER INFORMATION sheet PCT/ISA/210

3. ☐ Claims Nos.:
because they are dependent claims and are not drafted in accordance with the second and third sentences of Rule 6.4(a).

Box II Observations where unity of invention is lacking (Continuation of item 2 of first sheet)

This International Searching Authority found multiple inventions in this international application, as follows:

1. ☐ As all required additional search fees were timely paid by the applicant, this International Search Report covers all searchable claims.

2. ☐ As all searchable claims could be searched without effort justifying an additional fee, this Authority did not invite payment of any additional fee.

3. ☐ As only some of the required additional search fees were timely paid by the applicant, this International Search Report covers only those claims for which fees were paid, specifically claims Nos.:

4. ☐ No required additional search fees were timely paid by the applicant. Consequently, this International Search Report is restricted to the invention first mentioned in the claims; it is covered by claims Nos.:

Remark on Protest

☐ The additional search fees were accompanied by the applicant's protest.

☐ No protest accompanied the payment of additional search fees.

FURTHER INFORMATION CONTINUED FROM PCT/ISA/ 210

Continuation of Box I.2

Claims Nos.: 11

Independent claim 1 contains multiple alternative features defining 18 possible embodiments by 18 corresponding independent claims. Most of those alternatives, however, are either inconsistent with the subject-matter of the present application or not disclosed to such an extend that no meaningfull search is possible (See PCT International Search Guidelines Section IV: VIII-2.5 and 2.6). Therefore the scope of the international search is limited for the following reasons:

1. The first set of alternative embodiments of the opto-electronic device according to independent claim 1 where the stacked active layers are 'photon-absorbing layers' (eg. the opto-electronic device is a photo-absorbing device) can only further contain the features 'selectively absorbed' and 'extracting charge carriers generated in the absorbing layers'. All other further possible alternative features are not clear and supported by the desciption in the sense of Article 5 and 6 PCT in such an extend that no meaningfull search can be performed and thus are exluded form the international search.

2. The two further sets of alternative embodiments of the opto-electronic device according to independent claim 1 where the stacked active layers are either 'photon-emitting layers' or both 'photon-absorbing and photon-emitting' are not supported by the description, thereby rendering the claimed subject-matter unclear in such an extend that a meaningfull search is not possible. The description does not contain one clear and complete realization exhibiting either only photon-emitting properties or both photon-absorbing and photon-emitting properties. On pg. 34 of the description reference is made to the term Stacked Wavelength Selective Photodetector (SWASP) LED or Laser. This term renders the subject-matter unclear and ambigious since it is not clear what type of properties such a device should exhibit. Moreover, only the mentioning of the fact that the same concept could be used for light-emmitting devices through a particular, not further specified choise of parameters does not provide enough information for the examiner to determine the scope of the claimed subject-matter. These particular embodiments are not clear and supported by the description in the sense of Article 5 and 6 PCT in such an extend that no meaningfull search can be performed and thus are excluded from the international search.

3. For similar reasons as mentioned in section 1, the alternatives defined in the dependent claims 3,4,6,8,9,10 are only supported when this feature refers back to the corresponding embodiment in claim 1 such that it forms subject-matter consistent with the embodiments in the description. Therefore all features directly related to the photon-absorbing device, eg. 'absorbing properties', 'adjustable absorption' and the use of the photo-absorbing device as a solar cell, imager or light-valve, should relate to the embodiments not exluded from the search as discussed in 1. All other other combinations result in embodiments not clear and supported by the description in the sense of Article 5 and 6 PCT in such an extend that a meaningfull search is not

FURTHER INFORMATION CONTINUED FROM PCT/ISA/ 210

possilbe and thus are exluded from the international search.

4. Moreover, apart from the inconsistency and unclarity the alternatives introduce as discussed under section 3, the dependent claims 2-10 also contain features, which result in an unclear realization of the invention. Especially the terms relating to functional features such as: 'dimensioned to adjust', 'chosen such as', 'adapted such as', 'adapted to be capable of or to serve as' are only interpreted and searched to the extend that these features can be directly and unambigiously related to clear and complete realizations of the invention disclosed in the description and the drawings.

Consequently, the international search is limited to claims 1-10 insofar related to a stacked multilayer photon-absorbing optoelectronic device, taking into account all limitations as set out above.

The applicant's attention is drawn to the fact that claims, or parts of claims, relating to inventions in respect of which no international search report has been established need not be the subject of an international preliminary examination (Rule 66.1(e) PCT). The applicant is advised that the EPO policy when acting as an International Preliminary Examining Authority is normally not to carry out a preliminary examination on matter which has not been searched. This is the case irrespective of whether or not the claims are amended following receipt of the search report or during any Chapter II procedure.

INTERNATIONAL SEARCH REPORT

Information on patent family members

International Application No
PCT/EP 00/05590

Patent document cited in search report	Publication date	Patent family member(s)	Publication date
US 5689123 A	18-11-1997	US 6100546 A	08-08-2000
US 4975567 A	04-12-1990	NONE	
US 4705361 A	10-11-1987	JP 2618870 B	11-06-1997
		JP 63011909 A	19-01-1988
US 5646421 A	08-07-1997	CA 2127596 A	17-01-1995
EP 0812023 A	10-12-1997	NONE	

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